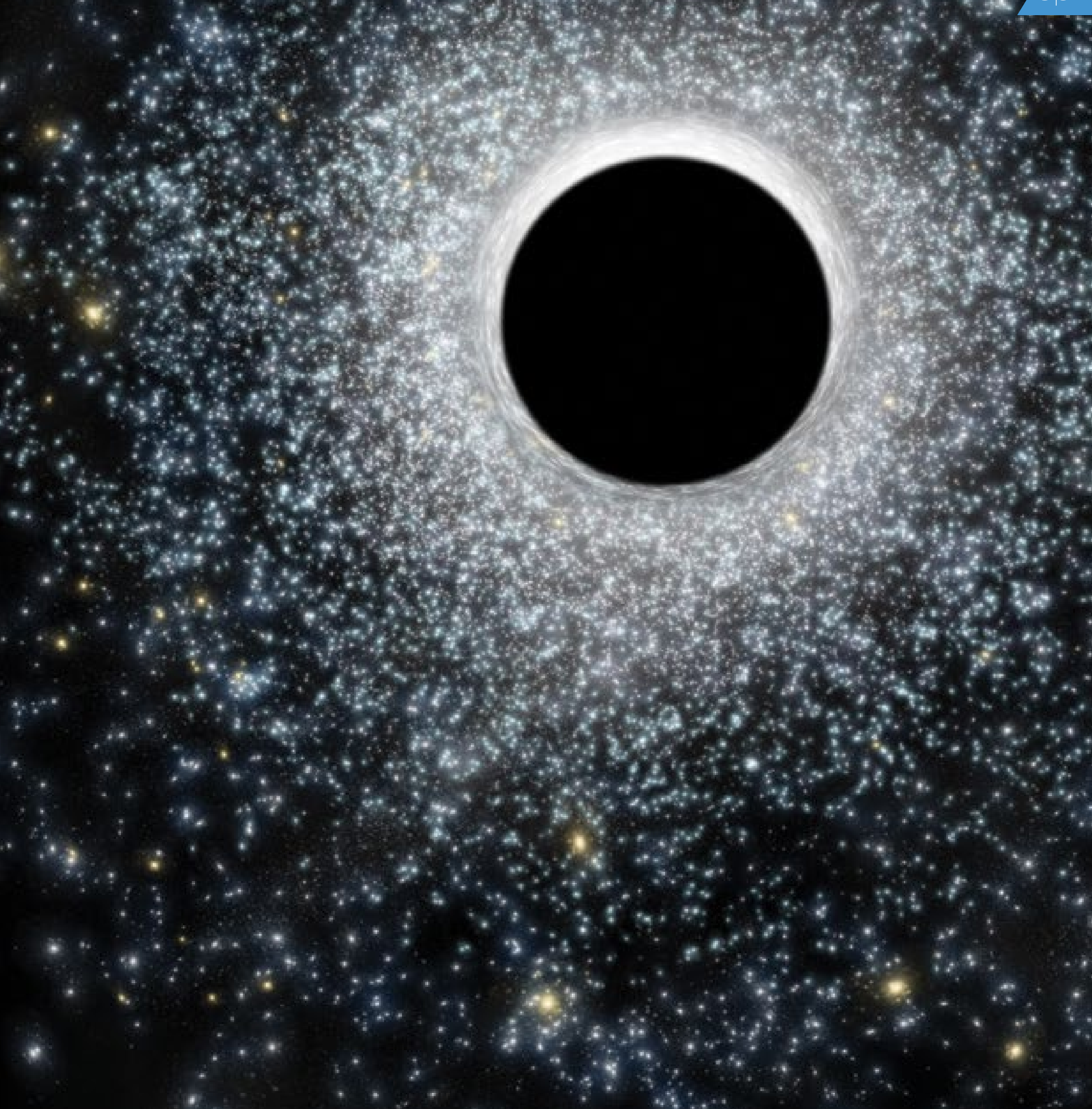
inside the Perimeter

spring/summer 2018



Remembering Stephen Hawking

The riddle of the quantum Sphinx

AI solves quantum challenges

Taming the Langlands program

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
Mike Brown
Dan Falk
Colin Hunter
Stephanie Keating
Robert Spekkens
Neil Turok

Copy Editors
Tenille Bonoguore
Mike Brown
Colin Hunter
Stephanie Keating
Sonya Walton
Natasha Waxman

Graphic Design
Gabriela Secara

Cover Illustration
Center for Astrophysics / M. Weiss

Photo Credits
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Mitch Altman
Michael Bennett
Mike Brown
Stephanie Keating
Jens Langen
John Matlock
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Jennifer Roberts Photography
Gabriela Secara
UCSB/Sonia Fernandez

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To subscribe, email us at
magazine@perimeterinstitute.ca.

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

IN THIS ISSUE

GOODBYE, DEAR STEPHEN

I was an undergraduate physicist in Cambridge when I was fortunate to attend Stephen Hawking's inaugural lecture as the Lucasian Chair, the position Isaac Newton once held. The lecture was provocatively titled: "Is the end of theoretical physics in sight?" Through a series of light-hearted vignettes, Stephen explained some of physics' greatest advances. He kept the audience on tenterhooks to the end, as we awaited his oracular answer to the question. When it came, it was as surprising as it was unambiguous. Yes, he said, the newly constructed theory of supergravity, developed by other theorists, was the answer. All that remained was to work out a few details. I left the lecture wondering if physics was really over and whether I should switch to another field.

Eighteen years later, I joined Stephen as a Professor at Cambridge. Supergravity had not worked out as the ultimate theory (but interest in it continues to this day). I knew something of Stephen's elegant and influential work combining quantum theory with gravity in the context of black holes and cosmology, and I was keen to interact with him and, if possible, to learn from him. So I presented a seminar on a topic I hoped might pique his interest – the birth of an inflationary universe. I showed how quantum effects in inflation, like a cosmic magician, allowed you to conjure an infinite universe out of a finite one. To my delight, after the lecture, Stephen said he found the ideas interesting and he wanted to discuss more. Thus began our work together, spending many wonderful afternoons scribbling on the blackboard and teasing out the technicalities. Even more wonderful, we became close friends.

There is so much to say about him, it's hard to know where to begin. It goes without saying that he was a brilliant scientist of the very first rank. The concepts he formulated and the questions he started to address, many decades ago, are so deep and farsighted that they continue to inspire the whole field. How can space and time be quantum? What happens inside black holes? What principles govern the universe? I feel today we are approaching the answers, guided in large part by observations that were largely lacking when Stephen pioneered the field. Even if the details of some of Stephen's favourite theories – like inflation and supergravity – don't survive, I believe that his basic intuition – that quantum mechanics will connect beautifully with gravity, and the combination will answer deep questions – will turn out to be right.

Despite Stephen's stature, he never became stuck in his ideas. He was open to questioning everything, to rigorous argument, and to finding new connections. It made working with him enormous fun; it was as if all the physical constraints on his body were mirrored by a total freedom and power of thought. You always got the sense, when discussing science with him, that in the next 30 seconds, we might change everything.

He loved speed and risks and jokes. And bets! In 1975, he bet Kip Thorne that black holes did not exist – a bet he lost. He bet John Preskill that black holes destroyed information. He declared himself wrong in 2002, and gave John an encyclopedia on baseball but encouraged him to burn it, saying that would be as useful as the information which survived an evaporating black hole. He bet me that cosmic inflation would be confirmed by future measurements – unfortunately, we never did settle that one.

Stephen loved the idea of Perimeter Institute. It was younger and much more of a gamble when I was approached to become its second Director. Taking the position would mean leaving Cambridge and Stephen behind, so I went rather gingerly to his office to tell him and ask for his advice. But when I described Perimeter's mission – to unify quantum theory and spacetime – his eyes literally shone. Although he said he would be sorry to see me go, I could tell he shared my excitement and would lend his fullest support. Which he did, time and time again.

First, he lent his name to our new building, the Stephen Hawking Centre. And then he visited, twice, despite the massive effort and risk involved, because he wanted to see for himself what this "grand experiment," as he called it, was like. He loved being here, having scientific discussions in the Bistro, and inviting many of us over to barbecues at his house. He met with everyone – the PSI students, the scientists, and countless visitors who wanted to be introduced to him.

In many ways, Perimeter epitomizes Stephen's aspirations and his vision. He believed, as I do, that the astonishing simplicity and unity in the universe cries out for simple, principled explanations.

The popular theories like inflation and supersymmetry – which Stephen, like most others, went along with – remain unconvincing and lack compelling evidence in their favour. Physics now has, I believe, to return to the basic challenges and questions that Stephen posed in the earliest and most fruitful phase of his career. There isn't a better place in the world for doing so than Perimeter. In many ways, we have taken on his scientific mission at a time when other places are either unable or have lost the confidence to do so. Stephen strongly supported the Centre for the Universe we have recently created here, kindly endorsing the Stephen Hawking Fellowship to which we hope to attract an extraordinary young cosmologist.

On Stephen's very first night in Waterloo, I invited him and his team out to a local restaurant. We shared a lovely, memorable meal together. When I went to pay, I was told that a regular patron (who insisted on remaining anonymous) had settled our bill, as a welcome gift to Stephen. Stephen was delighted, telling me that, on all his travels, such a thing had never happened to him before.

One fine afternoon, during Stephen's second visit to Perimeter, he and I decided to take a walk in the park behind the Institute. As we walked around Silver Lake by the public playground, a little boy started yelling, "That's Stephen Hawking!" We thought no more about it, but the next day I received an email from the kid's dad saying, "Was that really Stephen Hawking in the park?"

It turned out that the kid, although only six, had already read five of Stephen's books. When he told his mom it was Stephen, she said "it can't be!" But he desperately wanted to bring the books in and have them autographed. Stephen very graciously (and typically) agreed to meet the boy and thumbprint the books. The photo of the two of them together is one of my favourites. The thing I love about it most is that they're both wearing the same shirt! Two little kids at heart, driven by curiosity and a desire to have fun making sense of the world.

– Neil Turok

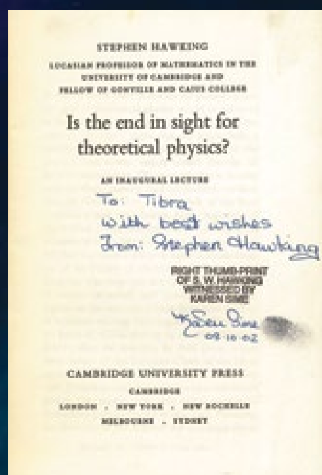
Remembering our friend
Stephen Hawking

1942 - 2018

***Ray Laflamme** was a graduate student under Stephen Hawking at Cambridge when he was tasked with proving a theory of Hawking's. The problem was, the theory turned out to be wrong.*

Stephen, although being well known and having an incredible reputation, with many people looking up to him, was a scientist. And science is very democratic. You discuss ideas, and ideas can be right or wrong. The math in theoretical physics tells you what is right and what is wrong. So I slowly, painstakingly, went through the math and showed that the original idea could not work. Fortunately, there was a colleague, Don Page, who had a very similar result to mine. We slowly convinced Stephen, and when he learned that he had made a mistake, he turned around and said, "You guys are right." He was incredibly gracious. I heard that he wrote letters of recommendation for me saying, "This guy has proved me wrong."

*PSI Fellow and cosmologist **Tibra Ali** was a graduate student at Cambridge when he came across a rare find.*



STEPHEN HAWKING

LUCASIAN PROFESSOR OF MATHEMATICS IN THE UNIVERSITY OF CAMBRIDGE AND FELLOW OF GONVILLE AND CAIUS COLLEGE

Is the end in sight for theoretical physics?

AN INAUGURAL LECTURE

To: Tibra
with best wishes
from: Stephen Hawking

RIGHT THUMB-PRINT OF S. W. HAWKING WITNESSED BY KAREN SIME

08-10-02

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I was a graduate student at Cambridge when I came upon Stephen Hawking's, "Is the end in sight for theoretical physics?", a bound version of the inaugural lecture he gave as the Lucasian Professor at Cambridge. It was about 10 pounds or so – way too expensive for my poor wallet – but I bought it anyway and kept it carefully packed away with my stuff. He was the head of my research group and we got used to seeing him every day. Often at department parties, he would get bored of talking to the bigwigs and just come and hang out with the students. Right before I graduated, I finally got up the courage to go and thank him during a party, and ask if he would autograph the book. In a day or two, I had his autograph on what would become my most prized possession. His secretary had also inserted a photo of him. I love that photo with his impish smile – and a copy of Marilyn Monroe's biography tucked into his chair.

***Imogen Wright** was a PSI master's student when Stephen Hawking paid them a visit.*

My mother doesn't exactly understand what I studied at Perimeter, but she has a massive photo of me chatting to Professor Hawking at my graduation on her wall, and I think that makes her prouder than anything else I've ever done.

Eugenio Bianchi was a Perimeter postdoctoral researcher when he used loop quantum gravity to re-derive the Bekenstein-Hawking formula for the entropy of black holes. Then Hawking came to visit.

I was in the Bistro having a coffee and Lee Smolin introduced me to Stephen Hawking. Stephen wanted to hear from me about this recent calculation of black hole entropy. I said I was absolutely happy to do that when they were free. They said, "Okay, in 15 minutes."

I didn't have time to freak out or over-prepare. I just had 15 minutes to think exactly what I would condense and explain. The first three questions [from Hawking] were very short: "Are previous calculations wrong?", "Is the area ensemble wrong?", and then "Which degrees of freedom?" They were precise questions, the kind you would love to get when you give a seminar: questions that would either kill the argument or make it stronger. Then we went on for three hours discussing, and after three hours they said: "Okay, we go on tomorrow morning." I was absolutely blown away by that.

When I met him that first time, I had the highest opinion one could have of a scientist. Meeting him and having questions directly from him on what I was doing – that's something I couldn't top. Many of his questions are still driving my research today.

Holly Hatch was Perimeter's Conference Coordinator during Hawking's first Perimeter visit in the summer of 2010, when she was asked to coordinate a day trip to Niagara Falls. It ended up being the first of many memorable interactions.

I first met Stephen in his office at PI, and I quickly realized that he was just a regular person – a parent and a grandparent. His days were full of complex science, but he knew that weekends were for having fun.

The Niagara Falls trip was memorable, particularly getting soaked on the Maid of the Mist while hoping my makeshift poncho-wrap would keep his computer – his main communication system – working. I got to know Stephen and his carers over the next six weeks, and they even watched the Canada Day fireworks from the backyard of my townhouse in UW grad student housing – the only place that nobody would find Stephen!

The most memorable outing we had, though, was to the African Lion Safari in nearby Cambridge. We were in a specialized rental van and I warned the group that we likely couldn't take it through the infamous monkey section (because they scratch the paint), but they kept insisting. I still remember our van, covered in monkeys, as Stephen's carers kept rolling down the windows to try to feed them bananas – all while an enormous male lion sunned himself a few feet from the van. They were having the time of their lives, but I was sure that I would be fired as soon as we got home. Instead, I was called into Stephen's office the next week and asked to plan a return trip so he could bring his visiting grandchildren.

Three new appointments bolster mathematics and cosmology

From the depths of space to the mathematical framework for physics, three new appointments to Perimeter's associate faculty are pushing to uncover big discoveries.

Cosmologist Will Percival, mathematician and computer linguistics researcher Matilde Marcolli, and mathematician Ben Webster will bolster the Institute's research and strengthen ties to partner universities. Perimeter now has 19 associate faculty cross-appointed with other institutions in Canada.

"These new appointments represent a major strengthening of the Institute's efforts in cosmology and in mathematics," said Perimeter Director Neil Turok. "Both are critically important avenues through which new insights into fundamental physics are being gained."

Turok added: "All the direct observational evidence we have on physics beyond the Standard Model and Einstein's theory of gravity comes from cosmology – for example, on dark matter, dark energy, and the nature of the big bang. Will Percival is a world leader in learning about fundamental physics from galaxy surveys, an area poised for major progress.

"Similarly, the new theoretical frameworks we now urgently need in order to connect quantum theory with gravity and the other forces of nature will require new mathematical frameworks and tools. Matilde Marcolli and Ben Webster are two of the most creative young mathematicians alive, working on areas which connect closely to theoretical physics. Their presence will ensure that Perimeter is a hotbed for brilliant mathematical thinking at the leading edge of physics."

WILL PERCIVAL: ALL EYES ON THE SKY

Will Percival also got his start in mathematics, and went to work in industry before realizing he wanted to pursue research that was part of a bigger picture than his day job presented. So he chose the biggest picture of all: exploring the universe at the largest scales.

Now, Percival works at the interface between observational and theoretical astrophysics and cosmology, with a particular interest in galaxy surveys. He has accepted two positions in Waterloo: as the holder of the new Lazaridis Research Chair in Astrophysics at the University of Waterloo and as an associate faculty member at Perimeter. He plans to build a UW research group rooted in the strengths of each institute, aiming to tackle some of the universe's biggest unsolved mysteries.

But observational measurements are only effective if there are good theories to test. "To complement a good observational group, you need a good theoretical group," Percival said. "Having the association between the new group at UW and the expertise available at Perimeter will be awesome."

MATILDE MARCOLLI: PUSHING MATHEMATICAL BOUNDARIES

Marcolli's eclectic research interests span mathematics, physics, and computational linguistics. She already had ties with Perimeter as a Distinguished Visiting Research Chair (DVRC). Indeed, her latest book, *Noncommutative Cosmology*, is based on collaborations with Perimeter researchers during her DVRC visits.

She left Caltech to take up a position at the Mathematics Department at the University of Toronto, cross-appointed with Perimeter.

Her decision to move north of the border was motivated by more than research; she was also growing increasingly concerned about rising anti-science politics and sentiment in the US.

"At present, it just feels great to be able to work and focus on science without having to keep worrying about that kind of threat," Marcolli said. "It is a privilege that people too easily take for granted."

BEN WEBSTER: EXPLORING THE CROSSOVER

Webster's work in pure mathematics always seems to cross into physics. His joint appointment to the University of Waterloo's Department of Pure Mathematics and to Perimeter Institute take that overlap to the next level.

Webster seeks connections between representation theory, mathematical physics, geometry, and topology. For the past decade, his focus has been on the mathematics of a particular quantum field theory that can be described using two different objects, or kinds of algebras. At Perimeter, he can work alongside researchers who tackle the same thing from a physics perspective.

"Understanding the mathematical relationship between those is a very difficult and strange question," he said. "For me intellectually, having the opportunity to come to PI was a big, big plus. The visitors, the ability to have conferences, the whole structure – it's a really unique thing."

– *Tenille Bonoguore*

FURTHER EXPLORATION

People of PI: Meet more of Perimeter's researchers at *insidetheperimeter.ca*

EMMY NOETHER FELLOWSHIPS EXPAND

Perimeter's flagship program to support and promote women physicists is being expanded thanks to funding from the Simons Foundation.

What started as a pilot project to support women researchers at pivotal career moments is set to become even more powerful thanks to a $600,000 US grant from the Simons Foundation.

Perimeter's Emmy Noether Fellowships have already brought 23 early- to mid-career researchers to the Institute for extended visits.

With this three-year funding, the program will expand both in size and depth: there is scope to appoint more researchers each year, and past participants will be able to return as Fellows in later years.

Perimeter will also intensify recruitment efforts in developing countries, establish the Simons Emmy Noether Fellows' Network (a peer resource to forge and support ongoing links between Fellows), and host a Simons Emmy Noether Fellows' Conference.

The long-term nature of the fellowships – which allow Fellows to build their collaborations over time – is a particularly powerful aspect of the program, said Perimeter Faculty member Bianca Dittrich, who chairs the Fellows selection committee.

"Long-term visits and the possibility of return visits will allow Fellows to pursue deeper research problems in these collaborations," she said. "By providing support for bringing family along, it also allows researchers to come for longer, and thus more productive, visits."

That interaction will not end when the Fellows return to their home institutes. "The Simons Emmy Noether Fellows' Network will be unique in connecting highly qualified women researchers in theoretical physics across the globe and to Perimeter Institute," Dittrich said.

Perimeter Faculty Chair Luis Lehner said the support from the Simons Foundation enables Perimeter to not only engage more researchers worldwide, but to help deepen the collaboration networks of each Fellow.

"We are now able to further amplify the scope and reach of this exciting program," Lehner said. "This will impact physics research at the Fellows' home institutions as well as PI. Science is an enterprise that can only get stronger by ensuring everyone has the chance to contribute to it."

Announcing this year's cohort

The 2018/19 Simons Emmy Noether Fellows are:

Ling-Yan (Janet) Hung (Professor, Fudan University): Janet Hung is a quantum field theorist with a particular interest in quantum entanglement and the AdS/CFT correspondence. She also works closely with experimentalists to probe topological order in quantum systems.

Valentina Forini (Lecturer, City University of London): String theorist Valentina Forini studies diverse aspects of gauge field theories using the AdS/CFT correspondence, and her work has impacted both sides of the string/gauge correspondence.

Karen Livesey (Assistant Professor, University of Colorado): Condensed matter researcher Karen Livesey works in the area of nano-magnetism. She has particular interests in magnetic domain walls, in very small magnetic swirls called skyrmions, and in creating models for interacting magnetic nanoparticles to match experiments.

Christine Muschik (Assistant Professor, Institute for Quantum Computing – University of Waterloo): Christine Muschik is a quantum information specialist who plans to launch an intensive effort exploring quantum simulations of lattice gauge theories, with an aim to develop new tools for basic science – specifically, quantum simulators – and to provide applications for near-term quantum devices.

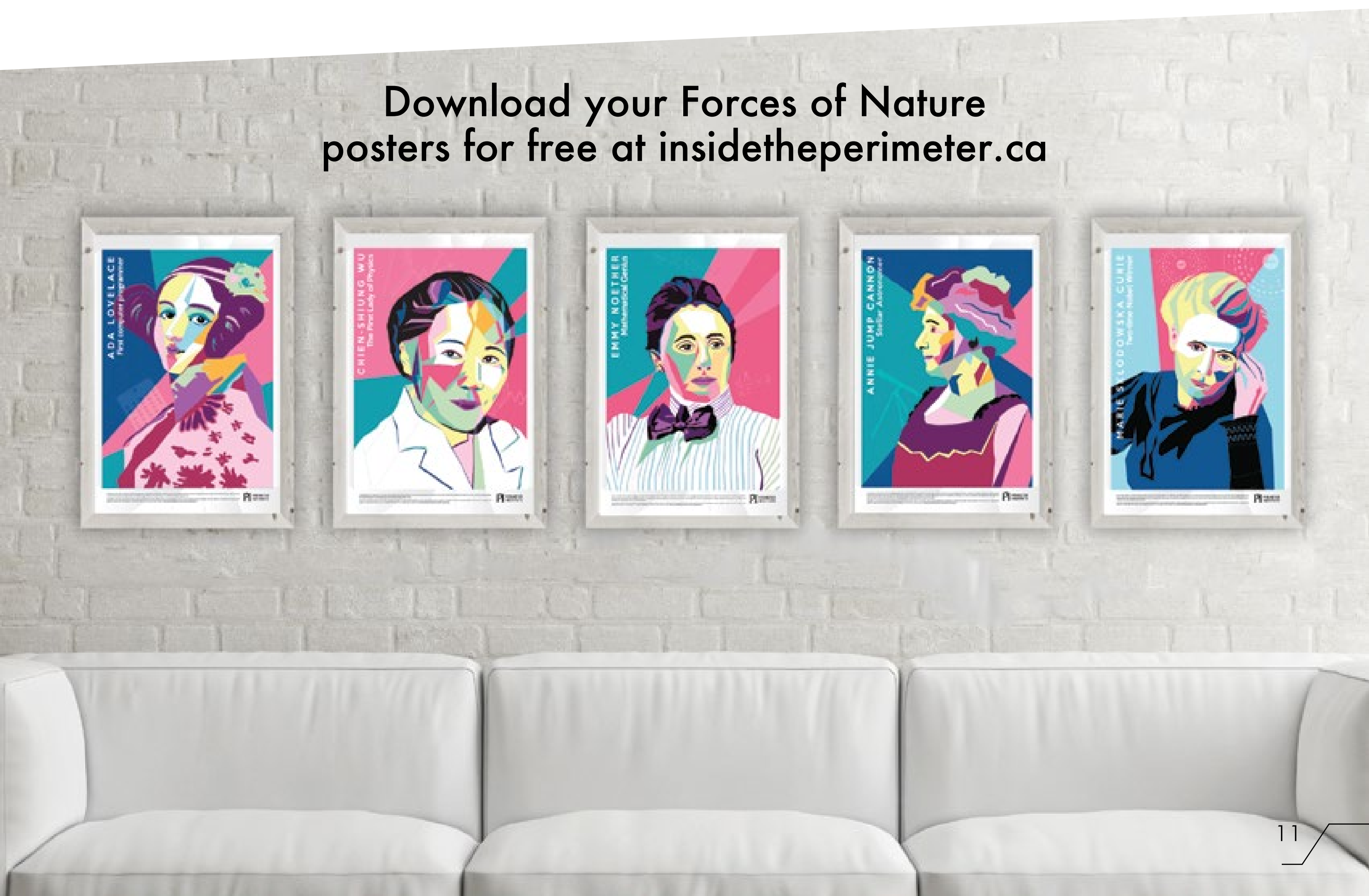
Phiala Shanahan (Assistant Professor, College of William and Mary): Particle physicist Phiala Shanahan recently launched a five-year research project into the quark and gluon structure of nuclei, with a particular interest in applying machine learning to numerical studies of the Standard Model.

Sherry Suyu (Max Planck Research Group Leader and Assistant Professor, Max Planck Institute for Astrophysics – Technical University of Munich): Astrophysicist Sherry Suyu uses strong gravitational lensing to shed light on dark energy, dark matter, and supermassive black holes. She plans to work closely with members of Perimeter's Centre for the Universe, and other Perimeter researchers.

– Tenille Bonoguore

FURTHER EXPLORATION

Find out more about Perimeter's Emmy Noether Initiatives at perimeterinstitute.ca/research/emmy-noether-initiatives



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California connections

Perimeter's Educational Outreach team partners with the California NanoSystems Institute at UCLA and Environmental Research Advocates to bring science resources to LA teachers.

Los Angeles is a city more likely to conjure up visions of Hollywood stars than neutron stars. But physics and the arts are not as disparate as they may seem.

Philanthropist and activist Denise Avchen, who co-founded Environmental Research Advocates (ERA) with her husband Terry Avchen, a prominent environmental lawyer, was inspired to support science education after seeing budding artists fall on hard times without a backup plan.

"When you're dealing with the arts, the impetus is creative. You're absorbing the world around you. And I find that in physics," said Avchen.

Now, teachers in Los Angeles are boosting their ability to engage students with science and math thanks to a growing partnership between Perimeter Institute and the California NanoSystems Institute (CNSI) at UCLA. The collaboration was made possible thanks to the vision and support of ERA, a global non-profit foundation dedicated to bringing financing and recognition to environmentally sustainable projects.

After visiting Perimeter and seeing its resources in action at a local classroom, Avchen knew California teachers and their students could benefit immensely from them. "It's such a great way to present the material," she said.

When she got home, Avchen reached out to educational and community leaders across LA, including CNSI, which regularly hosts events for more than 400 teachers in the area. In 2016, Perimeter's Educational Outreach team was invited to present a two-day pilot workshop for 50 teachers. The project was a resounding success and this year the workshop grew into a full-fledged conference.

In February, 43 educators from underfunded inner-city charter schools gathered at CNSI, staying overnight at the UCLA campus while they delved deeply into the process of science. Workshops, demonstrations, and activities spanned the full gamut of modern physics, from quantum mechanics to cosmology.

In addition to materials and supplies, teachers took home pedagogical strategies that they can use right away. "They loved the new deep science they learned. They could immediately take it back to their classrooms – that's really empowering," said Greg Dick, Perimeter's Director of Educational Outreach.

"These great teachers, the ones who take their weekends and drive long distances to come to a weekend workshop, are fighting for their students. They want the kids to have better lives," said Avchen. "That's what I'm hoping our collaboration will do – give kids a chance. Perimeter does that all over the world."

– Stephanie Keating

FURTHER EXPLORATION

Find all of Perimeter's free resources for teachers at resources.perimeterinstitute.ca

The riddle of the quantum Sphinx

Is a category mistake at the root of our troubles with quantum theory? Perimeter Faculty member ***Robert Spekkens*** *explores what we can learn from Egyptian hieroglyphs.*

A scientific hypothesis is compelling to the extent that it coheres well with other successful hypotheses and with the experimental evidence, as interpreted through the lens of one's hypotheses. When these are woven tightly together in a mutually supporting web of ideas, they are rarely the subject of controversy.

For quantum theory – the theory which describes all of fundamental physics with the exception of gravity – there is a staggering lack of consensus about its interpretation. There are many proposals for how to do so, but none has achieved sufficient coherence with the rest of physics to persuade a majority of researchers that it is correct. Why not? I believe that it comes down to a category mistake.

To commit a category mistake is to take some entity to be one type of thing when in fact it is another. In the case of quantum theory, most approaches have assumed that its central entity – the quantum state – describes reality. In my view, it actually describes incomplete information about reality.

It would not be the first time that a category mistake was an obstacle to progress in science. My favourite example comes from the story of the decipherment of Egyptian hieroglyphs, a problem that was known as "The Riddle of the Sphinx."

Egyptian hieroglyphs are one of oldest known writing systems. They emerged prior to 3,000 BC and were used continuously for more than three millennia. The last person in the ancient world who could read and write hieroglyphs likely died sometime in the 5th century AD. For the next 1,300 years, every inscription on every tomb, temple, monument, statue, or vessel that survived from the ancient Egyptian civilization fell silent.

The category mistake that stymied so many scholars' attempts to decipher hieroglyphs concerned the nature of a glyph. They were assumed to be ideograms representing an idea directly and pictorially, independently of any spoken language, like the symbols on airport signs. In fact, they were phonograms, representing the sounds of a spoken language. In retrospect, all of the attempts at decipherment under the ideographic fallacy, as it is now called, generated only nonsense. No progress could be made until this category mistake was corrected.

A question of "how?"

In 1799, Napoleon's army discovered the Rosetta Stone, which contained the same text in three different writing systems: hieroglyphs, demotic, and the Greek alphabetic script. Because scholars knew how to read the Greek text, they were confident that they knew precisely what the hieroglyphs on the Rosetta Stone must be saying. Nonetheless, the question remained of how they managed to say it.

The quantum formalism is similar. Even though we know what it says about the relative probabilities of different measurement outcomes in any given experimental arrangement, the question of how it manages to say this remains. For example, the equations specify the statistical correlations that arise for measurements on a pair of systems that are initially prepared together and then separated, an experiment first suggested by Einstein, Podolsky, and Rosen in 1935. To provide an explanation of these correlations, however, one needs to provide a causal account of how they arise. Is there a causal influence from one wing of the experiment to the other, or is it simply that the pair of systems act as a common cause, with no influence between the wings?

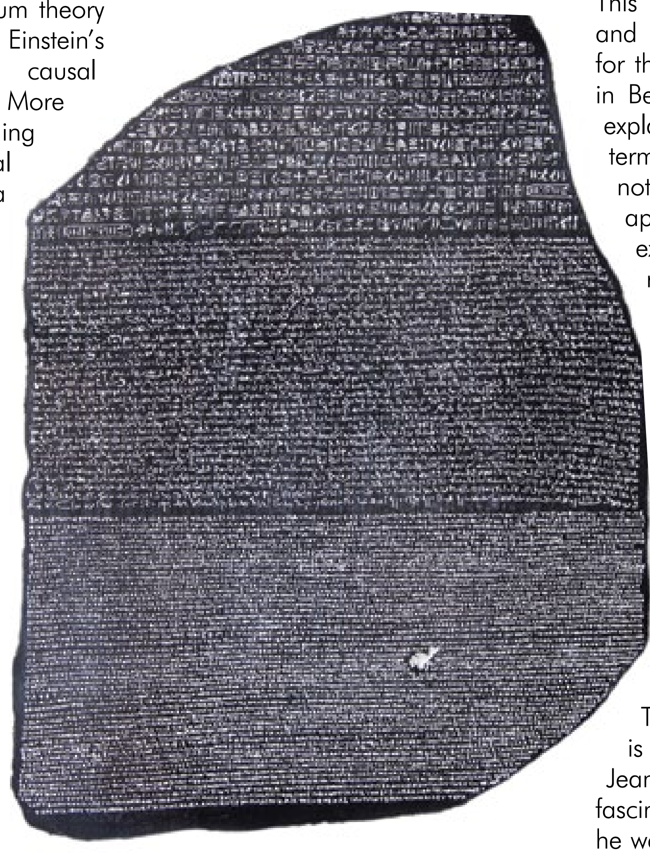
Getting the causal story right is critical if one seeks to extend quantum theory into new domains, such as Einstein's theory of relativity, where causal structure plays a critical role. More generally, scientific understanding is all about achieving causal explanations, not merely a description of correlations, so it is also critical for achieving coherence between quantum theory and the rest of science.

It turns out that the causal account of this experiment depends critically on the attitude one takes to the quantum state.

On the one hand, if one takes different quantum states to represent different ways the world can be, then because different choices of measurement at one wing of the experiment lead to different quantum states at the other wing, one must grant that there are causal influences from one wing to the other which travel faster than the speed of light. In other words, this interpretation leads to "spooky action at a distance" and tension with relativity theory.

On the other hand, if one takes different quantum states to represent different ways of having incomplete knowledge of the world, then the different choices of measurement at one wing can correspond simply to different ways of updating one's knowledge of the physical state at the opposite wing. This is because the physical states at the two wings are both determined by a common cause, so that learning about one implies updating one's information about the other. No spooky actions are required in this case.

We now know that there are certain fragments of quantum theory – containing only a subset of the full set of quantum states and measurements – which admit of an interpretation where every quantum state can be understood as a mathematical encoding of a probability distribution over a set of deeper physical states. These are called Clifford fragments.



Rosetta Stone

For quantum phenomena appearing in these fragments, the account of them that one obtains in this way is both compelling and coherent with the rest of physics – for instance, by not requiring any faster-than-light causal influences. Moreover, the Clifford fragments contain most of the phenomena that are thought to be characteristically quantum: entangled states, the collapse of the wave function, interference phenomena, quantum teleportation, the impossibility of cloning quantum states, wave-particle duality, and many others.

Is there any hope of pulling off this sort of explanation beyond the Clifford fragments? Not if we insist that incomplete knowledge of reality must be represented by a probability distribution.

This is what is shown by a famous 1964 "no-go" theorem due to John Bell. However, we need not insist on this. Perhaps the complex-valued matrices appearing in the quantum formalism provide a novel way of representing incomplete information about reality.

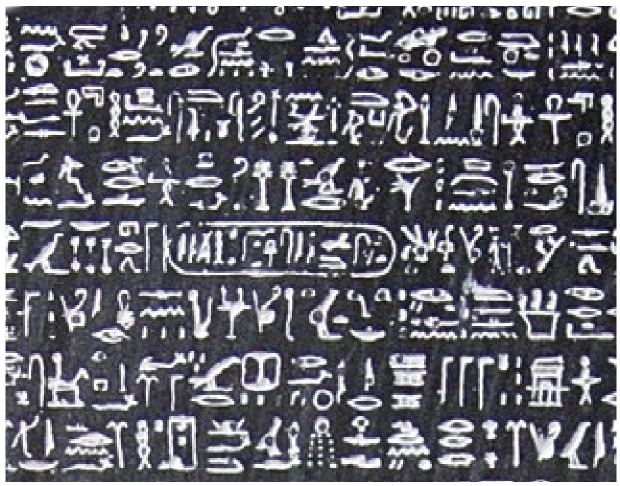
This idea is currently being pursued, and it is already apparent that even for the sorts of experiments considered in Bell's theorem, one can secure an explanation of the correlations in terms of a common cause. But it is not yet apparent how to make the approach work for every conceivable experimental arrangement. It is still a research program.

Nonetheless, the nature of the evidence against quantum states representing reality, at this moment in time, bears a strong analogy to the nature of the evidence against the ideographic interpretation of hieroglyphs just prior to their decipherment.

An ancient challenge

The hero of the decipherment story is a Frenchman by the name of Jean-François Champollion. Already fascinated by Egyptology as a youth, he went on to study languages, and, in 1808, acquired a high-quality copy of the Rosetta Stone inscription. Early on, he deduced that the demotic text on the stone was just a cursive form of the hieroglyphic text. Parts of the demotic text had been previously recognized to phonetically encode the sounds of foreign names appearing in the Greek text, such as the Greek Macedonian name of Ptolemy, so Champollion reasoned that this would be true of the hieroglyphs as well.

He focused on strings of glyphs that were encircled by ovals – dubbed "cartouches" by Napoleon's soldiers because of the similarity to the shape of their bullet casings. Counting the number of signs appearing there, he became convinced that the cartouches contained the name of Ptolemy rendered phonetically. He then found confirming evidence for the phonetic values he had obtained, in a cartouche containing the name of Cleopatra in a different hieroglyphic inscription that had an accompanying Greek text. He found yet more evidence for his values by identifying the names of other Pharaohs in the cartouches of other hieroglyphic texts.



A Rosetta Stone cartouche

Incredibly, this progress did not lead Champollion to overcome the ideographic fallacy. Instead, he reasoned that it was only in the exceptional circumstance of writing proper names that they were to be interpreted phonetically.

In the early 1820s, Champollion was still working feverishly on the problem. He was not sleeping much and hardly eating. The solution continued to elude him until, on a fateful day in 1822, he decided to focus on the glyphs outside the cartouches and see what would happen if he attempted to read these phonetically as well.

Bear in mind that it was not known what language was spoken by the ancient Egyptians, and if nothing of it had survived, then a phonetic reading would have been impossible. But something had survived. The language of the Egyptians had continued to be used in the liturgical tradition of the Coptic Christian Church, even after Arabic became the everyday spoken language of Egyptians following the Arab conquest of Egypt in 642 AD. As it happened, Champollion had studied the Coptic language. So when he attempted a phonetic reading of the glyphs in the rest of the Rosetta Stone, he began to recognize the verbs, nouns, pronouns, and grammatical forms of Coptic. That was his Eureka moment. He sprinted across town, burst into his brother's office, shouted "*Je tiens l'affaire!*" (I have it!), then collapsed out of exhaustion.

Champollion's phonetic reading of hieroglyphs has stood the test of time because it has the kind of coherence with other evidence that makes it nearly impossible to dispute: the meaning of the hieroglyphic script on the Rosetta Stone is found to match that of the Greek text, and similarly for other scripts that have Greek counterparts; the contents of hieroglyphic inscriptions fit with their archaeological and historical context; and the notion that Coptic is a descendent of the language of the ancient Egyptians fits both linguistic and historical evidence.

The lesson for quantum theorists

For the Clifford fragments of quantum theory, the interpretation of quantum states that coheres best with the rest of physics is the one that interprets them as states of knowledge rather than states of reality. This parallels the discovery that the glyphs within the cartouches are phonograms rather than ideograms.

For the totality of quantum theory, there is good reason to believe that quantum states can still be interpreted as states of incomplete knowledge. Such knowledge is not represented by probability distributions, but a more exotic formalism, the precise form of which is not yet clear. This parallels the fact that, unlike proper names that are pronounced similarly in many different languages, a phonetic reading of the glyphs outside of the cartouches required Champollion to identify the specific language spoken by the Egyptian scribes. For proponents of the research program described above, unearthing the novel formal language for expressing incomplete information of reality – our Eureka moment – is still to come.

There are many other problems in physics for which the proposed solutions are not yet compelling because they are not yet embedded in a web of mutually supporting relationships with the rest of physics. For these, the story of the decipherment of hieroglyphs should prompt us to reflect more deeply about our presuppositions: could they contain a category mistake?

– Based on Robert Spekkens' Perimeter Public Lecture on February 7, 2018

Watch it on Perimeter's Youtube channel:
www.youtube.com/PIOutreach

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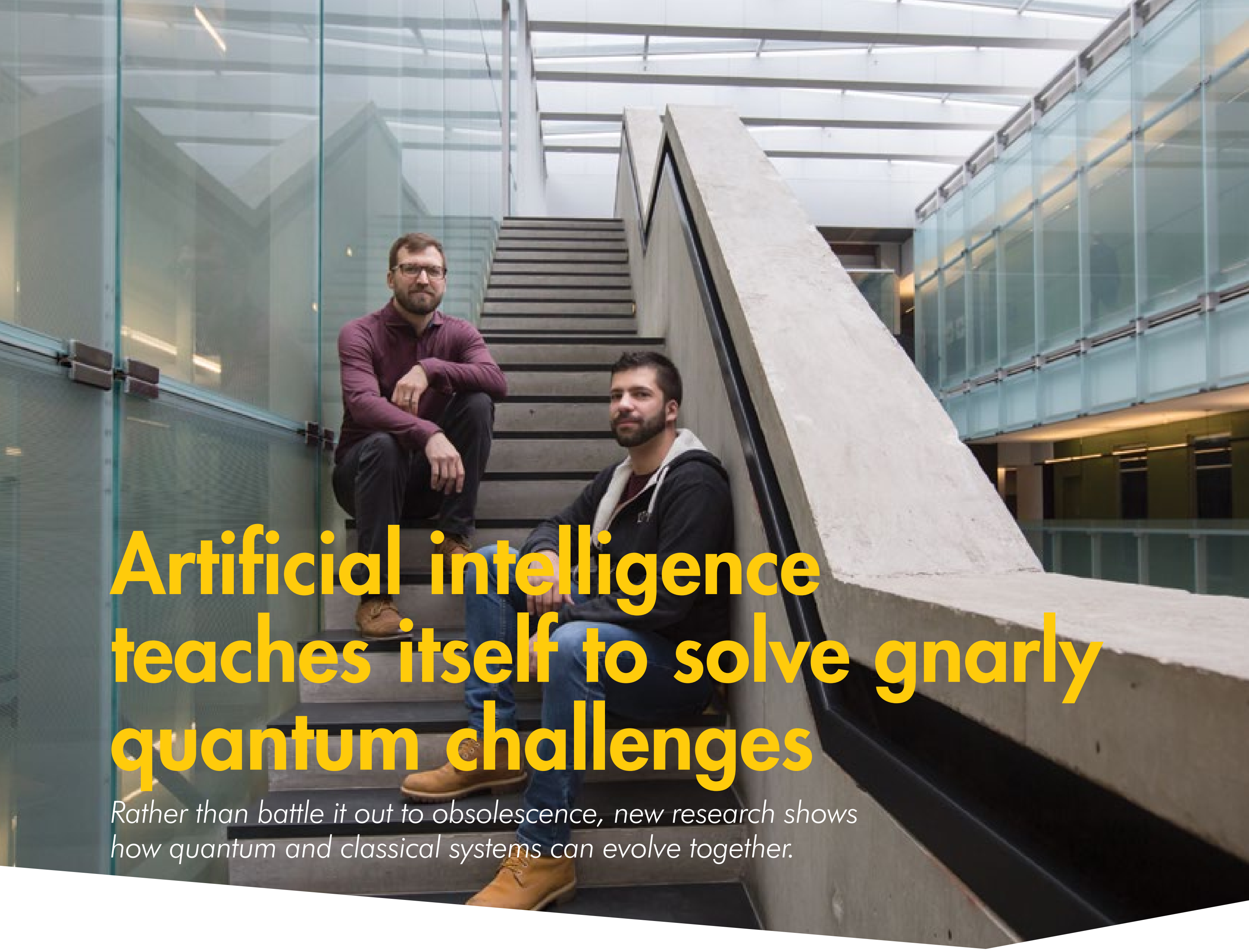


Artificial intelligence teaches itself to solve gnarly quantum challenges

Rather than battle it out to obsolescence, new research shows how quantum and classical systems can evolve together.

In popular culture, quantum computing is often painted as an ultra-powerful technology that will first outrace, and then replace, its classical counterpart. In reality, though, the two are inextricably linked.

We use classical computation and simulations to develop and design today's nascent quantum devices, which are then nested within a much larger framework of classical computers.

The effort to advance these different technologies – which both fuel and rely on each other – resembles something like a dance. Movement is required on both sides. It takes the best in classical computing to advance quantum capabilities, yet each leap in quantum computation demands more of its classical partner.

This *pas de deux* recently took one more step thanks to a paper published in *Nature Physics* by researchers at Perimeter Institute and the University of Waterloo, with collaborators at ETH Zurich, Microsoft Station Q, D-Wave Systems, and the Vector Institute for Artificial Intelligence.

The team applied an artificial intelligence (AI) to a particular problem in quantum computing: working out the state of a quantum device using only snapshots of data gleaned from experimental measurements.

This is a gnarly challenge. The state of a quantum system contains all the information about that system. However, you can only extract some information at any one time. ("This is partly due to the uncertainty principle and mostly just due to the nature of quantum mechanics itself," noted Perimeter PhD student Barak Shoshany in an answer on Quora.)

Why is it worth the hassle? Because this ability – to know, and therefore exploit, a quantum state – is crucial to quantum computing. Until we can do that, our ability to scale the small quantum devices that we do have, or manufacture more robust quantum computing hardware, remains limited.

Currently, we ascertain the state of quantum devices using a process called "quantum state tomography," or QST. Using imperfect snapshots of the system as a starting point, researchers mathematically backtrack until they can ascertain the full quantum state at the moment the measurements were taken.

This "reverse-engineering" approach is performed with complex algorithms that require a considerable amount of data input and manipulation. It is a significant challenge because of the huge number of incomplete snapshots required to perform the reconstruction.

In the paper, "Neural-network quantum state tomography," Perimeter associate PhD student Giacomo Torlai and Perimeter Associate Faculty member Roger Melko (pictured left), along with collaborators, applied the same process, but had a cutting-edge AI neural network do the heavy lifting.

They embraced unsupervised machine learning – essentially, an AI that learns for itself. The AI learned how to combine the measurements of the quantum hardware to create its complete quantum mechanical description.

"Our algorithm only requires raw data obtained from simple measurements accessible in experiments," Torlai said. "The idea is to build a general and reliable tool to assist the development of the next generation of quantum simulators and noisy intermediate-scale quantum technologies."

Retooling AI

In industry, neural networks are often used to mine big data. Torlai and collaborators reversed that dynamic: they took an industry-standard neural network, called a restricted Boltzmann machine, and applied it to theoretical research.

It is part of the broader "quantum machine learning" program in which theorists and experimentalists use machine learning to design and analyze quantum systems.

Torlai, who came to Waterloo specifically to work with Melko, first used machine learning to study quantum error correction for topological quantum systems.

In this latest research project, he designed the machine-learning methods to perform neural-network QST. The team then performed the tests using controlled artificial datasets generated from a number of different quantum states.

They started with a standard (but still complex) system, in which interacting quantum spins are arranged on a lattice. This model is used in quantum simulators based on ultra-cold ions and atoms, and its tomography is very difficult using traditional approaches. The self-learning AI worked.

The team then progressed to increasingly difficult challenges until they reached one of the most complex things to calculate: entanglement entropy.

Entanglement entropy is associated with the information that is lost when you isolate a region to study its quantum properties. By "cutting out" part of the system to study, you inevitably leave some entangled partners out of the equation. This corresponds to missing information, which corresponds to entropy.

Entanglement entropy provides important information about interacting, many-body quantum systems, and is of great interest in condensed matter physics and quantum information theory. But assessing entanglement entropy in experiments is fiendishly difficult.

The team found that the neural network was able to provide an estimate of entanglement entropy using simple measurements of density, which are accessible using today's experimental capabilities. "This approach can benefit existing and future generations of devices ranging from quantum computers to ultra-cold atom quantum simulators," they write.

Putting it into practice

Unlike the majority of approaches designed to understand quantum hardware – which are tailored to the specific regime – the team's AI is platform-agnostic. The neural network, they write, is general enough to be applied to a variety of quantum devices, including highly entangled quantum circuits, adiabatic quantum simulators, and experiments with ultra-cold atoms and ion traps in higher dimensions.

"Our approach can be used to directly validate quantum computers and simulators, as well as to indirectly reconstruct quantities which are experimentally challenging for a direct observation."

Melko and colleagues have already put this to the test. In a follow-up paper published as a preprint on the arXiv, the AI was applied to real data. "The original paper only tackled pure quantum states. We had to account for the fact that experiments can be a little more noisy, they can be more dirty and uncontrolled," he said. "It worked great."

It's one more step in what he expects to be a long and fruitful exchange between classical and quantum computation.

"In the future, when we scale these quantum devices, it's going to be the AI that can watch the quantum system," Melko said. "The most adaptive, most efficient algorithms will nurture the quantum computers. It's going to build them, it's going to design them, and when they're running, the AI is going to interface with them."

The key to it all – the music for the dance – is data. With the right AI and enough data, this work shows that it is possible for a general-purpose neural network to learn, probe, and analyze a quantum system, regardless of its theoretical underpinnings.

And that is a good thing, says Torlai. After all, data is an essentially limitless resource.

"We are now at a turning point, with the possibility of generating large amount of data with the quantum hardware currently operational," he said. "The data will always be truthful."

– Tenille Bonoguore

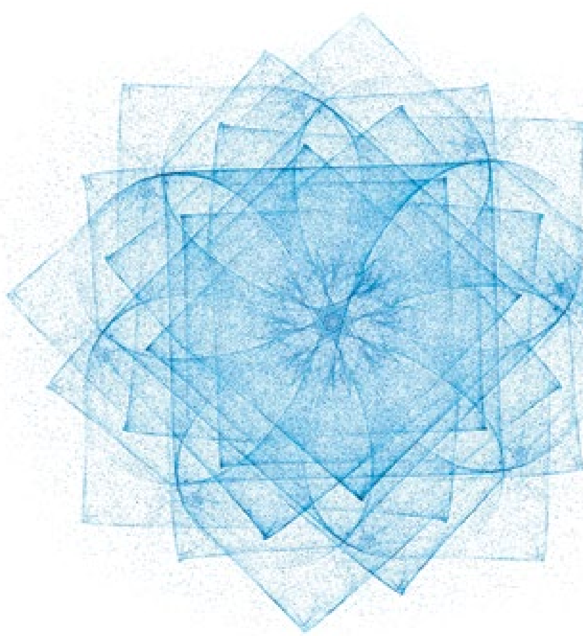
Taming the Langlands program

Perimeter researchers are pulling from physics and mathematics to connect two ways of understanding nature, writes **Dan Falk**.

Almost 400 years ago, Galileo declared that nature is "written in the language of mathematics." Since that time, the relationship between mathematics and science – especially physics – has only strengthened. Unfortunately, the universe doesn't come with a guidebook that explains which mathematical ideas can be used to explain which natural phenomena.

Sometimes, the connections are relatively straightforward. For example, Galileo found the mathematical formulas that govern the motion of simple pendulum, and of balls rolling down an incline. But as the physics gets harder, so does the math. When Newton tried to understand how one variable changes moment by moment with respect to another, he found he needed an entirely new kind of mathematics (what we now call calculus; as it happened, Gottfried Leibniz developed it at the same time). And when Einstein was developing his general theory of relativity, he found that he needed to make use of non-Euclidean geometry – which, luckily, had been invented around 60 years earlier by the German mathematician, Bernhard Riemann.

Indeed, today's mathematics can be so involved that it's hard to tell if two branches of mathematics are related to each other, let alone to the physical world. And vice-versa: in some areas of physics, we're still in the process of discovering which mathematical tools are needed and learning how to develop them.



This tangle is giving rise to a rich interplay across disciplines, in which physicists can learn from mathematicians, and, perhaps surprisingly, mathematicians can also learn from physicists. That is where Davide Gaiotto comes in.

Fittingly, Gaiotto holds the Krembil Galileo Galilei Chair in Theoretical Physics at Perimeter. His particular interest is quantum field theory (QFT), a theoretical framework for modelling the behaviour of subatomic particles. (As Gaiotto points out, it makes more sense to talk about them in the plural, quantum field theories.)

The origins of QFT go back almost 100 years, to the first attempts to combine quantum mechanics with theories such as electromagnetism. Since then, QFTs have proved to be incredibly successful – and invaluable in describing the real world. They underlie the Standard Model of particle physics, the framework that accounts for the known forces of physics (with the exception of gravity). Some of its predictions agree with observations to an accuracy of one part in 10^{10}. And yet, there's still a great deal about QFT that remains to be discovered. "We still understand very little of it," Gaiotto says. He adds, "It's really hard!"

The good news is that mathematicians and physicists are collaborating more than ever before – a collaboration that was sparked around 20 years ago, Gaiotto says, when string theory (an attempt at a quantum theory of gravity) first gained widespread attention. "In the process, mathematicians got interested in quantum field theory, and physicists got interested in certain mathematical tools," Gaiotto says.

Many of those tools involve something called the Langlands program. Named for Canadian mathematician Robert Langlands, the Langlands program involves proposed connections, or bridges, between a number of seemingly disparate branches of mathematics. In particular, it suggests bridges between number theory (the study of integers, especially prime numbers) and analysis (an umbrella group of ideas involving continuous curves and surfaces, of which calculus is the best-known example).

At first glance, these seem quite different. Numbers are discrete entities, while curves and surfaces are continuous; it's not immediately obvious why they should be related at all. But Langlands figured we just weren't looking hard enough. Back in 1967, when he was 30 years old, he wrote a letter to André Weil, one of the mathematical luminaries of the time. In the 17-page letter, Langlands outlined the nature of the bridges as a series of conjectures, urging Weil to consider them as "pure speculation." He added: "If not – I am sure you have a waste basket handy."

The waste basket would not be necessary. Langlands was on to something. (Earlier this year, he was awarded the prestigious Abel Prize, often considered the mathematical equivalent of the Nobel.) In fact, mathematicians have spent much of the past half century trying to prove the various conjectures that make up the Langlands program; it is sometimes referred to as a "grand unified theory of mathematics."

A key issue is the nature of the connection between these mathematical structures and the physics of quantum field theory. What, exactly, does it reveal about the physical world?

"They [the mathematicians] are still far from being able to understand quantum field theory completely," Gaiotto says. "But at least they're already learning to do calculations that the physicists didn't know how to do." The mathematicians are also getting something in return: "They're slowly coming to accept this idea that quantum field theory is a big lump of knowledge that is waiting to be unpacked."

Jim Arthur of the University of Toronto, one of Canada's leading mathematicians and a former student of Langlands, agrees. "To me, it seems there's a very striking analogy between the Langlands program and quantum mechanics," he says.

The equations that crop up in the Langlands program, he suggests, are akin to the famous Schrödinger equation, which governs the evolution of quantum mechanical systems.

"If you apply the same kind of analysis to [the Langlands program] that physicists apply to the Schrödinger equation, you get the analogue of energy levels," he says. "You get discrete numbers."

In other words, the mathematicians who have immersed themselves in the Langlands program may have something to offer the physicists who have been struggling to make sense of QFT; quite possibly, they can help physicists better understand these exotic mathematical structures.

Quantum mechanics describes things that come in discrete units, like the energy levels allowed within an atom. Meanwhile, most physical theories involve fields, which are continuous. Anything that can help connect these two ways of parsing nature could pay off in the world of particle physics.

For Gaiotto, the key idea is something called the geometric Langlands duality – a reformulation of the original bridge conjectures expressed in terms of algebraic geometry (the study of complex, non-Euclidean structures). In 2006, Edward Witten of the Institute for Advanced Study and Anton Kapustin of Caltech discovered a connection between the geometric Langlands duality and S-duality, a property of certain quantum field theories such as supersymmetric gauge theory.[1] (S-duality is somewhat analogous to the connection between electricity and magnetism, explains Miroslav Rapčák, Gaiotto's PhD student: if you swap electrical and magnetic charges, the mathematical structures stay the same. S-duality is like a supersymmetric version of that.)

Gaiotto's work builds on what Witten and Kapustin had begun. Witten and Kapustin had been investigating the dualities that link various mathematical structures in the geometric Langlands program, and their relation to physical objects. They'd managed to show that QFT predicts the existence of such relationships, and that certain mathematical objects would encode the properties of particular physical objects.

They also identified which physical objects were responsible for the most important mathematical objects on one side of the duality. However, they lacked a generic method for translating from the physical side to the mathematical side, and for working out a physical description of the objects whose existence they'd predicted.

Later, in collaboration with Witten, Gaiotto and his colleagues were able to identify these dual physical objects, but couldn't immediately find a way to compute the corresponding mathematical objects.

"For me, the puzzle was that I had these quantum field theory configurations, which clearly had implications for the Langlands program," says Gaiotto. "But I could not do calculations with them, and that bugged me." He says that last year he finally had the tools needed to "sidestep the main computational obstruction," as he puts it. His breakthrough revealed the connection between the physical and mathematical structures. And with that, he was in a position "to do actual calculations."

The breakthrough involved applying vertex operator algebra to the problem. Vertex algebras, Gaiotto explains, are like Rosetta Stones that can help the mathematicians and the physicists understand each other. Gaiotto showed that calculations involving physical objects could be treated as vertex algebra calculations; he created a "dictionary," as he puts it, for "mapping physical objects to vertex algebra objects."

The result sheds a light on "a web of mathematical dualities, which extend

[1] Supersymmetry (SUSY) proposes a relationship between two basic classes of elementary particles: bosons, which have an integer-valued spin, and fermions, which have a half-integer spin. In supersymmetry, each particle from one group would have an associated "partner" particle in the other, the spin of which would differ by a half-integer. These super-partners have not yet been observed in nature. Gauge theories are a class of quantum field theories in which the variables that describe the field remain unchanged, or invariant, under certain transformations. This property gives the theory a certain symmetry, which in turn restricts how the field can interact with other fields and particles. A supersymmetric gauge theory is a theory that's consistent with supersymmetry, and which also has internal gauge symmetries.

and clarify the original geometric Langlands [program]," he says.

It's a significant breakthrough, according to those who work in the field – "quite spectacular," as Witten describes it. "He has made remarkable progress in understanding the geometric Langlands correspondence," Witten said by email. "It is amazing to me how he has been able to bridge the gap between what could be understood by physics-based methods and what the mathematicians are able to appreciate."

Gaiotto's work has attracted widespread interest, and was the focus of a three-day workshop at Perimeter in May, titled "Gauge Theory, Geometric Langlands, and Vertex Operator Algebras." Witten and other leading specialists were in attendance.

With geometric Langlands now at least partially tamed, Gaiotto hopes the collaborations between mathematicians and physicists will continue. "I see very fruitful developments in the future, in the interaction between physicists and mathematicians," he says. After all, the mathematical structures he's been exploring are very rich; there's much more out there waiting to be discovered. It's like those old maps from the Age of Exploration, he suggests. "There are a bunch of trade routes that you've been following, a few pieces of land that you understand, but 99 percent of the map is just sea monsters."

He also hopes that more light will be shed on quantum field theories. That's tricky, though, because the mathematics is very rich, and – Galileo's dictum notwithstanding – it's far from clear that all of it applies to the universe we live in. It may very well be that only some parts of the Langlands program will bear fruit that turns out to be relevant for physicists. But Gaiotto's okay with that.

"Personally, I'm interested in quantum field theory as its own subject," he says. "At this point, I like it enough that, even if it didn't have any applications to physics, I would still pursue it. The fact that it has applications to physics is an extra bonus."

Dan Falk (@danfalk) is a science journalist based in Toronto. His books include The Science of Shakespeare *and* In Search of Time.

My favourite equation

We all have our favourite things.

Physicists explain the universe through the symbolic language of mathematics, so it makes sense that they have special fondness for certain equations. We asked scientists to reveal which equation stole their heart, and why. Here are seven – you can find more at insidetheperimeter.ca

$$F = \frac{Gm_1m_2}{r^2}$$

Natalie Panek

Rocket scientist, MDA Corp.

"This equation inspired me to write a high school research project on using rotation curves of galaxies to estimate the amount of dark matter in the universe, which introduced me to the inspiring work of Vera Rubin. That paper was the launch point for my career in aerospace."

$$\mathrm{AdS} = \mathrm{CFT}$$

Pedro Vieira

Theoretical Physicist, Clay Riddell Paul Dirac Chair at Perimeter Institute,
and Visiting Professor at the ICTP South American Institute for Fundamental Research

"Our best definition of quantum gravity in a box (in AdS) is given by quantum field theory without scale (the CFT). This works amazingly well for toy models, simplified theories used as theoretical physicists' playgrounds. Is this also how the universe works?"

$$L = 4\pi\sigma R^2 T^4$$

Emily Levesque

Astronomer, University of Washington

"The luminosity-radius-temperature relation for stars is a deceptively simple equation: it demonstrates that a star's luminosity increases with both its radius and its temperature. Because of that, it's very elegant and easy to understand."

$$F = ma$$

Rob Moore

Assistant Director, Stanford Institute for Materials and Energy Sciences

"I can't think of another equation that has had a more dramatic impact on our history and our world. So much of what we have built around us started with knowing F=ma."

$$S = k \log W$$

Sean Carroll

Astrophysicist, Caltech

"Ludwig Boltzmann's definition of entropy appears on his tombstone. This deceptively simple equation relates the underlying macroscopic world to the emergent world of our experience, and helps explain the arrow of time. Also, having an equation on your tombstone is pretty gangster."

$$\left(\frac{\dot{R}}{R}\right)^2 - \frac{8\pi G}{3}\rho - \frac{1}{3}\Lambda c^2 = \frac{Kc^2}{R^2}$$

Ethan Siegel

Astrophysicist, Lewis & Clark College

"The first Friedmann equation describes how, based on what is in the universe, its expansion rate will change over time. If you want to know where the universe came from and where it's headed, all you need to measure is how it is expanding today and what is in it. This equation allows you to predict the rest!"

$$\Delta S > 0$$

Marina Cortês

Cosmologist, University of Edinburgh

"The second law of thermodynamics is both profound and mysterious. As the great quote by Arthur Eddington says, you can escape any laws but 'if your theory is against the second law … there's nothing for it but to collapse in deepest humiliation.'"

People of PI:

Ghanaian trailblazer Prince Osei

After obtaining the first PhD in mathematics granted by the University of Ghana, Prince Osei is tackling complex problems in quantum gravity and setting an inspiring example for the next generation.

Prince Osei's path to academia has been marked by a stubborn, almost pathological, avoidance of what others suggested he do.

Now, as a researcher tackling some of the most difficult problems quantum gravity has to offer, his instincts have proven correct and his example is motivating other aspiring mathematical physicists in his native Ghana.

Growing up in Akim Oda, a small town in the eastern region of Ghana, Osei spent much of his time playing football in the streets or going hunting. When he was only 10 or 11, his father – an accountant at the local secondary school, as well as a farmer – feared he was becoming troublesome and sent him to boarding school in Ghana's capital city, Accra, to "become proper."

Suddenly separated from his family, Osei had to learn to do things for himself, including fending off bullies. He found it difficult settling in, but emerged with a deep-rooted sense of independence.

In junior high school, Osei's math teacher put a simple equation on the board and asked someone from the class to try to solve it. Osei volunteered, but made a mistake in his solution.

"He put me in front of the class and told me that, if I can't solve this problem, I can't go anywhere, and that I'm dumb," remembers Osei with a laugh. "That night, I said, 'No, I'm going to prove to this man that I am not stupid.' I got out all the math books at my disposal and I read a lot."

He also sought help from friends who were stronger students, even bribing one with food in exchange for tutoring. "At the end of the term, I got higher marks than he did," laughs Osei.

Top marks became something of a theme. Osei finished junior high at the top of his class and elected to go to the country's best high school for science, pleasing his father, who hoped he would go to medical school. The only problem? Osei hated biology. "I had to make a conscious effort to make sure I was getting low marks in biology and 90-100 in math," he recalls. "At the end of the term, I showed the report to my dad and told him, 'Look at the biology. I am not good. I am not doing well. Look at math! I'm excelling.'"

Osei ultimately convinced his father of his preferred path and began studying mathematics at the nearby University of Ghana, taking some courses in theoretical physics as well. He stuck around for a master's degree, settling on quantum gravity as his area of focus after searching online for the most difficult unsolved problems in mathematical physics.

"Getting stuck and struggling for a long time and finally ending up with some nice result is satisfying," explains Osei. "I enjoy studying mathematics. I get excited. I shout when I get nice results."

A chance meeting

Toward the end of his master's, Osei had a chance meeting with Bernd Schroers, a professor from Scotland's Heriot-Watt University who also works on quantum gravity. While vacationing in West Africa, Schroers showed up in the University of Ghana's mathematics department during a discussion on differential equations. After chatting with Osei, Schroers asked to see his master's thesis.

"He stood out there in the sun and he was flipping through, and we were talking," says Osei. "After looking through for a while, he asked me, 'Do you mind if I supervise your PhD?'"

This might seem a serendipitous encounter, but Osei politely declined. Most of his colleagues had gone to North America to earn their PhDs, and that's where he envisioned himself going as well.

But Schroers, it turns out, is a little stubborn as well. It took months, many emails, another visit to Ghana, and a trip to Edinburgh for a workshop on quantum gravity and noncommutative geometry, but Osei eventually agreed to work with him.

Between 2009 and 2012, he spent three months per year in Edinburgh, as well as a little time at the African Institute for Mathematical Sciences (AIMS) in South Africa and at Perimeter Institute, but most of his time was spent at the University of Ghana – a school that had not awarded a single PhD in mathematics since its founding in 1948.

"I was the first PhD [in mathematics] to be awarded by the university after 65 years," says Osei. "Before I got my PhD, the youngest person with a PhD in the department who was Ghanaian was 65 years old."

After spending three years helping to build AIMS-Ghana as its Academic Director, Osei arrived at Perimeter in August 2015 via the Fields-Perimeter Institute Africa Postdoctoral Fellowship. A year later, he became a full-time postdoctoral researcher. "I had always wanted to have some time here," says Osei. "I had a lot of ideas in my head and I was looking for the time to get away and work on those ideas, and this was the perfect environment for me to do that."

A new quantum hub

Those ideas largely concern quantum algebra and an algebraic approach to problems in quantum gravity – in particular, the role of quantum groups in noncommutative geometry and topological quantum field theory.

He's also recently been interested in topological quantum computing, because of its relation to quantum gravity. It's an area he will be able to explore more in his new role as the Project Developer of Quantum Leap Africa (QLA). Based in Kigali, Rwanda, QLA is an information science and quantum technology hub created by AIMS to deliver high-impact research in big data analytics, quantum computing and quantum information technology, and smart systems design.

"The idea is to set up a world-class research centre in Africa," explains Osei. "Africa missed the Industrial Revolution. We missed the Digital Revolution. But there's a Quantum Revolution on the horizon and we don't want to miss it. The idea is to set up this new research centre to, in fact, lead the Quantum Revolution."

For now, Osei is just excited about the opportunity at QLA, but he ultimately wants to return to his native country and help build up the mathematics department at the University of Ghana. Last year, four years after Osei obtained his PhD, the university conferred three more PhDs in math.

"There are lots of young people behind me who have been inspired," says Osei. "The aim is to just focus on my assignments and try to achieve my goals, and then definitely it will naturally encourage."

– Mike Brown

G7 Sherpas hold planning sessions at Perimeter

In preparation for the 2018 G7 Summit in Quebec, representatives from each G7 nation assembled for two days of planning sessions.

In the ascent toward the 2018 G7 Summit, Perimeter served as base camp for representatives of world leaders from each of the Group of Seven (G7) nations.

In January, the personal representatives of leaders from each of the G7 nations gathered at Perimeter to plan for this year's Summit, to be held in Charlevoix, Quebec, in June.

Perimeter, the organizers said, exemplifies values underpinning their discussions: collaboration, openness, diversity, and the power of big ideas.

"Perimeter Institute is world-renowned. There are researchers here from all over the world and it is a beautiful setting in which to have a meeting of this kind," said Peter Boehm, who is the Deputy Minister for the G7 Summit and the personal representative of the Canadian Prime Minister.

The G7 Summit is an annual gathering where leaders of the Group of Seven democracies address global issues and opportunities to advance economic prosperity, equality, diversity, and the path to a more sustainable future.

Several months prior to the Sherpa meeting, Perimeter Director Neil Turok and Founder Mike Lazaridis shared ideas with Boehm on topics related to the G7, particularly regarding access to excellence for brilliant young people, the advancement of women, and building capacity in skills that will help drive the future economy.

During a break from their private sessions, the Sherpas met and talked with Perimeter researchers and students from their home countries.

Neil Turok said it was an "honour and a privilege" for the Institute to be chosen as the site of the planning sessions.

"Our task is to bring the brightest minds together, from around the world, and give them the opportunity and the challenge to interact, collaborate, and solve important problems," Turok said in a recorded greeting to the guests.

"A marvellous future awaits, if only we can take care of ourselves and our planet. We are relying on you, and our global leaders, to show the necessary wisdom."

– Colin Hunter

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REMODELLING SCIENCE

Researchers are seeing cracks in the structure of science. The solution, they suggest, could be to create a new, open-plan approach with room for everyone.

Ask a young researcher what is most frustrating them right now, and they might not point to a complex formula or an intractable theory. Rather, many are vexed by something much larger: the structure of science itself.

As society embraces the likes of open data, makerspaces, and collaborative processes, the historical foundations of science – university departments, pay-walled journals, group membership – are starting to feel increasingly out-dated.

A growing number of scientists argue that changing not just how we do science, but how we share it as well, would unlock vast new opportunities. This new kind of science, they envision, would be open in both process and in practice.

Other fields have already embraced the ethos of openness: "open software" (think Linux and GitHub) is now well entrenched after arriving on the tech scene in the late 1980s, and "open innovation" is on the rise. "Open science," however, is only now starting to gain traction.

A recent gathering at Perimeter Institute aimed to give that effort a boost. The three-day "Open Research" conference brought together 30 scientists, designers, and entrepreneurs to map out an alternate, open reality, and to identify paths that could lead there.

For co-organizer and physicist Matteo Smerlak, this is not an esoteric issue. His cross-disciplinary work intersects with several specialties, which means he's often facing a steep learning curve. For established research, one can turn to books and monographs, but few authoritative resources exist for cutting-edge topics. People must instead rely on a flood of research papers – many of which can be overlapping or contradictory. In recent years, that flood has become an unruly torrent thanks to the proliferation of online journals and the concurrent rise in predatory journals.

Meanwhile, the "publish or perish" ethos of academia means young researchers feel pressure to devote crucial years to creating a publishing track record. This often means sticking to "safe" incremental science that's likely to be publishable, and eschewing riskier work that could lead to bigger scientific payoffs. Compounding these issues is the increasing complexity of science itself.

By removing impediments that keep people out of research or muddy the flow of ideas, Smerlak believes that science could become more global and innovative. "A lot of science is really knowing what the good problems are. It's not only the skills and it's not only the data; it's being part of a conversation that is contemporary and alive," he said.

Despite their brilliance, researchers in developing countries are too often limited to working on old problems, he said. Much cutting-edge work begins as a conversation at a conference or institute. If you're not physically there, or are not already on the radar of those involved, you're left out of the loop.

"We have the internet now," said Smerlak. "There should be ways to open up the problems as they are being invented or raised, and make that open to external contributions. There's expertise out there that we're not leveraging."

(Perimeter Institute's PIRSA database

is trying to close that gap by sharing cutting-edge lectures and discussions for free.)

But getting scientists to take the plunge into open research – particularly in fields where data is typically protected, such as biology – is like waiting for the first penguin to dive off an ice floe, said Benedikt Fecher, head of "knowledge dimension" research at the Alexander von Humboldt Institute for Internet and Society.

While penguins are afraid of being eaten by a shark, scientists are worried that others will use their data to publish first (and thereby get ahead in the race for tenure or grants), or that they won't receive adequate credit for their ideas. That can make people who otherwise support the idea of open research reluctant to then follow through on it, Fecher said in his workshop presentation.

"There is an *ideal* of openness, and still a space to identify where it's really worth it and relevant," he said.

Complexity demands collaboration

Science is becoming more complex, and so are the problems scientists are facing. From astrophysics to epidemiology to climate change, the volume of data streaming in from experiments is opening windows on complex problems humans couldn't tackle in the past.

Where scientific advances used to be made by individuals or small teams, the complexity of today's breakthroughs requires global collaborations, said conference co-organizer Bapu Vaitla.

As a research fellow at Harvard University's T.H. Chan School of Public Health, Vaitla explores the linkages between two extremely complex systems: ecosystem health and human health. It's heavily collaborative work that encompasses everything from theoretical modelling to marine science.

"I think the acceleration of scientific progress is strongly dependent on our ability to create cooperative networks," he said. "By democratizing the awareness of the problem and inviting everyone to come help solve it, we find that problems are solved quicker, errors are remedied quickly, and science moves forward at a faster rate."

This doesn't just impact new and emerging projects. One of the key challenges for open science – and one of its greatest promises – is finding a way to connect people to science that is already under way. The more people we can connect, the better off science will be, says Simon DeDeo, who runs the Laboratory for Social Minds at Carnegie Mellon University.

"Every scientist in the developed world – Canada, the United States, certainly in Europe – we constantly get emails from young scientists in places like India and China, who are seeking to connect with the kind of science we do here," DeDeo said.

"Those kinds of connections, that democratization, that globalization of science, cannot be sustained by a model that was produced or really invented in 1830."

Science has been through such revolutions before. In the late 1600s, the Royal Society of England was founded, with the motto "*nullius in verba*" (take no-one's word for it). This built on the Republic of Letters and encouraged the sharing of ideas. Then came the rise of the journal, and with it the drive to publish results.

"We have a sense that we need something new," DeDeo said. "One of the big challenges, and one of the big opportunities, for us to solve is not just open data, not just free access to publications, but a larger question of how do we rethink collaboration, how do we rethink the openness of science for the 21st century?"

Startups on the scene

Thomas Landrain has seen the impact of open research first-hand. He's a synthetic biologist who started an underground "hacker space" lab called La Paillasse during his PhD, starting out with a handful of people, some refurbished lab equipment, and a basement squat.

The years that followed produced extraordinary results. The first project – created during the European horse meat scandal – was a cheap genetic diagnostic test to determine types of meat. Next came a collaboration with the State University of New York (SUNY) to work on biodegradable electronics; a project to produce ink using bacteria instead of petrochemicals (which was spun off into the startup Pili); and a NASA-funded project to design a low-cost, open-source bioreactor.

"When we opened the lab, I was expecting mostly biologists to come, but most of the people were non-biologists. They were people that wanted to do biology but never could," he said.

In 2014, La Paillasse moved to official premises in central Paris. A year later, it partnered with pharmaceutical company Roche to launch the Epidemium program, using big data to analyze cancer epidemiology. More than 300 people took part, most of them professionals working outside of science. One leading project was done by a team of data scientists who work in a bank. Another involved Marthe Gautier, the long-retired co-discoverer of Down syndrome.

Thomas Landrain in the early days of La Paillasse.

"We're not talking about citizen science," Landrain said. "With citizen science, you have to over-simplify a problem to make it affordable for people to play with it. Here, we bring the raw aspect of research in its complexity. Whoever wants to come at it, then come at it."

It didn't matter to the La Paillasse founders how rigorous the science was. The point, he said, was simply to challenge themselves and to work out what infrastructure is needed in order to do research and produce innovations. So far, it's led to robust results. "Every time we tried to work in a community manner in a very open, collaborative state, it worked marvellously well," he said.

Landrain has now launched Just One Giant Lab (JOGL), a research and innovation lab that aims to partner with academia, corporations, foundations, and non-profits to tackle massive social and environmental issues. He sees the efforts as a complement to – not a replacement for – academia.

"We need academic researchers, we need professional researchers. [But] that monopoly should not be there," he said. "Knowledge is infinite, so why not have also an infinite number of researchers?"

The need for cohesion

JOGL is just one of the organizations already moving into the open-research space. Conference attendees also included representatives from various knowledge-sharing and open-research startups, including Open Parallel, CTRL Labs, and Knowen.

These early, tangible forays into open research can be seen as a promising endorsement of the idea, but they pose issues as well.

Without a dominant platform, the scientific community risks splintering among a dozen or so technologies. If so, the barriers between platforms would defeat efforts towards collaboration. Researchers will remain in silos, separated by technological walls and limited awareness of each others' work.

Who pays for open research is another unsolved question. Right now, most researchers also teach or work in industry. At Landrain's labs, researchers are volunteers, relying on their day jobs to make a living. "People do it benevolently because they know it's going to be useful for the greater good," he said. "There is no exclusivity. Everything is based on open data; everything you produce is open source. We make it clear that we're not going to pay anybody, but we're going to provide you the chance to have fun and learn, and to be able to express your talents or imagination."

In the push towards open research, there is also a danger of inadvertently propagating one of the thorniest issues plaguing science today: its lack of diversity. As University of British Columbia microbiologist Rosie Redfield pointed out, those who make the norms shape them.

Today's science tends to favour a certain kind of person: privileged, educated, first-world, often white, usually male. (For example, a recent paper in *Nature Communications* showed that women do not get the same speaking opportunities at conferences.) Without more diversity at these nascent stages, there is a risk that the same biases will be baked into whatever tools and processes are created for open research.

Redfield – who keeps a blog detailing her lab efforts, and was the only woman presenting at the three-day conference – says higher diversity does not require lower scientific standards. It just requires awareness and vigilance.

"You have to counteract your intrinsic, implicit, unconscious biases," she said. "This isn't a male thing. We all have these unconscious biases. It's just that women are more aware of how women are being harmed by those biases, and we are working harder to overcome them.

"It's not enough to be well meaning. It's not enough to be well intentioned. You have to actively work on yourself."

Dividends are mostly for the young

So far, the most vocal pushback to open research has – as would be expected – come from the establishment.

Journals don't want to relinquish their control over scientific communication, and the massive profits that come with it. More senior researchers who have devoted their careers to assembling particular datasets are hesitant to openly share them.

It's mostly young researchers who are pushing for change, said Vaitla. "From this conference, the main takeaway for me has been that, more than creating tools, the real bottleneck to spreading open science is about shifting the norms," he said.

Perhaps surprisingly, Vaitla sees theoretical physicists as particularly well placed to help lead the charge. "Theoretical physicists don't deal as much with datasets in the general sense that we understand them, as do other fields. The sharing of data is less of a concern," he said.

"I think theoretical physicists in particular can be an interesting vanguard for this movement because they can identify a subset of problems that are perhaps a little bit easier to solve and create some momentum around."

For Smerlak, the "Open Research" conference was a small first step. All participants recognized that much work lies ahead if their vision is to come to fruition, but both academics and startup founders seemed eager for the challenge. The conference attendees plan to produce a white paper from their discussions, in order to prompt further discussions and actions.

"Whether you look at this from a distance or you're trying to make it happen, there's a strong desire to come together," Smerlak said.

"Open-source software is driven by a philosophy that's quite explicit and broadly shared by the main actors in the field. Scientists have had a philosophy of sharing ideas, being skeptical, reproducing results, trying to falsify results. There's no reason to think that we couldn't have a common philosophy when it comes to open research."

– Tenille Bonoguore and Stephanie Keating

FURTHER EXPLORATION

Watch the talks at pirsa.org/C18005

How to build a better future

In 2015, the United Nations established a global set of sustainable development goals (SDGs) to end poverty, protect the planet, and ensure prosperity for all by 2030. The challenge now is to turn those goals into action.

At the 2018 Waterloo Global Science Initiative (WGSI) summit, held in April, a diverse group spanning disciplines, sectors, and generations gathered to chart a course towards implementation in Canada and abroad.

Over three days of discussion and debate, they devised a robust, community-focused ecosystem that could support and promote the 17 SDGs. Together, they created the Generation SDG Communiqué, a preliminary set of recommendations, with a white paper to follow in 2019.

"Mobilizing Canadian society by building stronger and more equitable communities will not only help us achieve these targets, it can provide a long-term vision for Canada and its people," the Communiqué notes.

Visit wgsi.org/generation-sdg/summit-recap to read the Communiqué, watch the keynote presentations, and follow the project's progress.

The Waterloo Global Science Initiative is a partnership between Perimeter Institute and the University of Waterloo.

Generation SDG

WGSI Waterloo Global Science Initiative

UPCOMING CONFERENCES

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June 11-13

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July 9-20

Foundations of quantum mechanics
July 30-August 3

Higher algebra and mathematical physics
August 13-17

Conferences are continually being added.

Check **perimeterinstitute.ca/conferences** *for the latest.*

"Aim high, work hard, and bring your swagger"

"Inspiring Future Women in Science" event delivers bold dreams and reality-checks for science-loving teens: the world is full of possibilities, but you'll have to work hard for them.

"More women in science today means more women in science tomorrow. That's not only good for women – it's good for society."

– Mona Nemer, Chief Science Advisor, Government of Canada

How does one become a scientist? It's a simple question with a complex answer. Much like the process of science itself, the route from student to STEM professional is often punctuated with serendipity, intuition, wrong turns, and the occasional Eureka moment.

Leading astronomer Emily Levesque had to choose between her love of the stars and her love of the violin. Jesse Popp studied to be a veterinary technician before realizing it was a passion for biology that got her out of bed each day. General surgeon Monica Torres had to completely re-do her medical training when she came to Canada from Colombia. And mechanical engineer Martha Lenio built an eclectic career around the hope of becoming an astronaut. (She's still working on it.)

When 200 young women gathered to celebrate International Women's Day at Perimeter Institute's "Inspiring Future Women in Science" (IFWIS) conference in March, uncertainty and ambiguity were common themes.

But so, too, was the message that STEM is for everyone. During keynote speeches, a panel discussion, and a "speed mentoring" session with professionals across the STEM spectrum, the message was loud and clear: passion and perseverance can take you a long way.

Keep doors open

Eugenia Duodu is a chemist. She also grew up in a low-income community in Toronto, where her only ideas of being a scientist involved being old, male, and white.

While she loved science, she didn't consider it seriously until she took a bio-tech class at high school. "I killed it, and I loved it. I started to feel very confident," she said. Yet her guidance counsellor advised her against a science-heavy course load, cautioning that it might be too hard.

With her mom's adamant support, Duodu enrolled in those high school science courses anyway, and flourished. Then she enrolled in science at university, and flourished again. Slowly, she gravitated more and more towards chemistry, and ended up pursuing her PhD in therapeutics. But that was not the end of the story.

"Throughout my PhD, this question was still plaguing me: 'What are you doing with your life?'" she said.

"I still didn't know. A common myth is that your path is clear – you know because you're studying something. But I was still very much involved in my community. For a long time, I felt like these worlds [science and community] had to be separate. I was putting science in a box, and I was putting scientists in a box."

In the end, she has combined her passions as the CEO of Visions of Science, a non-profit that provides STEM outreach to youth in low-income communities.

"The ways I was solving things in the lab was applicable to how we can solve things all over the world," she said.

"You can be many things. All of the components of yourself, you bring to the table. Bring that strong."

The future of science

For the teens in the audience and watching online, the discussions opened their eyes to the huge variety of STEM careers, and to the hard work it takes to succeed.

Eema Kagoma, a Grade 12 student at St. John's College in Brantford, wants to be an architect. Before the event, she had assumed that following that career path would require setting aside her favourite subject: chemistry. Now, she's keen to pursue chemistry as an elective at university.

"I'm interested in biomimicry in architecture. I'm interested in all the different sciences and how I could meld them into what I'm studying," she said.

The sheer variety of STEM careers took Amanda DeGasperis by surprise. "You can't always judge the job by the title. Jobs that I thought were certain things were actually completely different. It was really interesting," said the Grade 11 student at St. Elizabeth Catholic High School in Vaughan.

Many of the students were surprised – and relieved – to discover that it's okay to not yet know what they want to study. Indeed, keeping an open mind means they won't close doors before they need to.

"You think that people who are so successful must have known from their childhood, but in actuality they didn't," said Serina Ykema-King, from Glenview Park Secondary School in Cambridge.

"It's nice to hear, because you go through high school worrying about what you want to be when you grow up. It's more about living in the moment and just trying your best today, because tomorrow you're going to find your path."

Seeing the potential

All of the speakers agreed on one major point: there is more to STEM than meets the eye. Sadly, though, most youth don't really get to see that varied landscape.

Mechanical engineer Martha Lenio didn't know what an engineer did when she enrolled in the program at the University of Waterloo. She wanted to be an astronaut, and figured it'd be handy to be able to fix the spaceship.

"When I was their age, I didn't know what engineering was," Lenio said after giving her keynote speech. "I think that's still a problem. People don't know what engineering or science jobs look like, or that if you do one thing at university, it is possible to do a lot of different jobs out of one degree."

She can attest to the variety of opportunities engineering can open up. Her unusual career has included teaching elementary school in Ghana, working on solar energy in Australia and Canada's north, and leading a NASA-sponsored mission in a "fake space" dome in Hawaii.

It's not the kind of pathway you could plot out from the start. Rather, it built and grew because Lenio was open to both opportunity and uncertainty.

"There's not one right way to go through engineering," she said.

And as for those goals of being an astronaut? Like the students in the audience, Lenio is still dreaming big. "There's still a possibility. There's going to be another call for astronauts in four years. Maybe…"

– Tenille Bonoguore

FURTHER EXPLORATION

Watch all of the talks from "Inspiring Future Women in Science" on Perimeter's YouTube channel Youtube.com/PIOutreach

Linamar Corporation was the Presenting Sponsor of IFWIS 2018.

The incredible MRI

They are commonplace now – with more than 46 million scans a year performed in the US and Canada – but magnetic resonance imaging (MRI) scanners still seem halfway to magic. They can look inside bodies to show not just bones, as X-rays do, but soft tissues like the brain, muscles, and organs, without delivering harmful radiation. Using incredible computations that turn raw data into moving images, MRI scans can show tiny details of a beating heart, or even the shape of thought as blood moves to the most active parts of the brain.

Dozens of physicists, doctors, medical researchers, and engineers laid the foundations for MRI in science and built technologies on top of them. There are patents, egos, and at least five Nobel prizes. But at the very beginning of the story, the incredible MRI owes its existence to a boy named Izzy and the fact that astronomy begins with an "A."

Robert Oppenheimer, Isidor Rabi, H. M. Mott-Smith, and Wolfgang Pauli at Lake Zurich, Switzerland

Credit: AIP Emilio Segrè Visual Archives, Fermi Film Collection

Izzy was born Israel Isaac Rabi, and rechristened Isidor when he enrolled in public school. His parents were Austrian immigrants and Orthodox Jews, devout and poor. They lived in Brooklyn, New York. Young Rabi was imaginative and bookish. He had already memorized all the books in his house and schoolroom – mostly Biblical creation stories and Yiddish folktales – when he spotted a classmate carrying a volume he didn't recognize. Where had it come from? The public library. It was 1908, and Rabi was 10. The world was about to change.

In the tiny Carnegie Library, Rabi started in the A's and quickly read all the children's fiction. The next shelf was non-fiction organized by topic, beginning with an astronomy book about Copernicus and his model of the solar system. "That was what determined my life more than anything else," he wrote decades later. "Reading that little book. It was so beautiful, so marvellous. So simple!" He gave his bar mitzvah speech on the physics of electric lights.

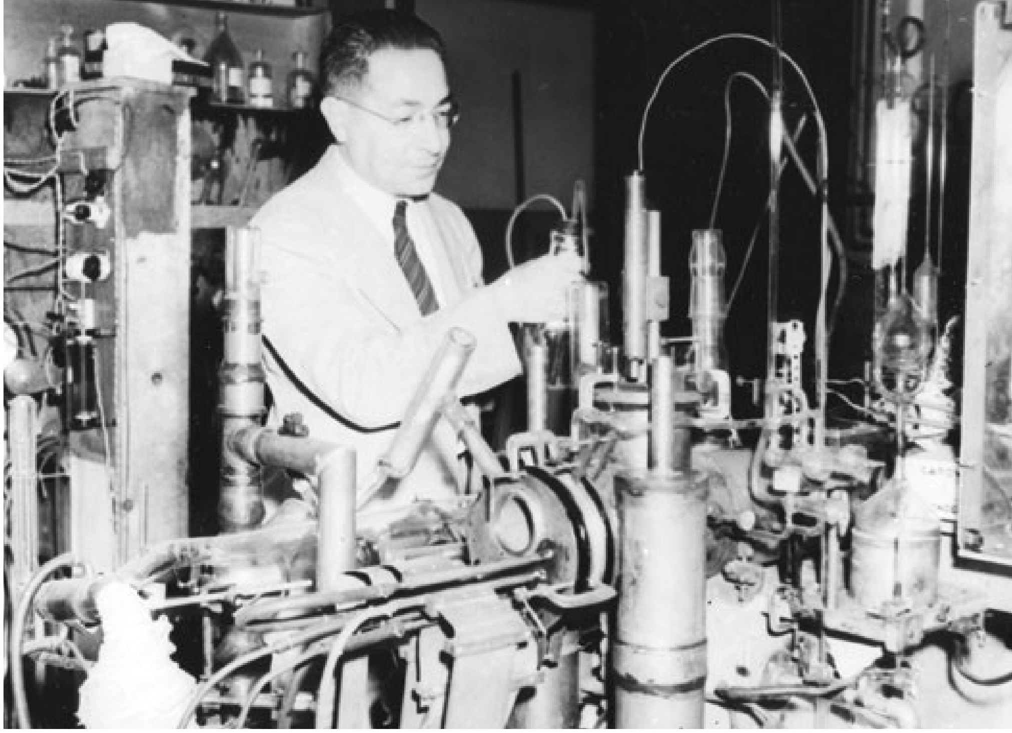
Rabi went on to study chemistry and then physics, earning a PhD in 1926. He spent two years in Europe immersing himself in the new and booming field of quantum mechanics, working with such giants as Bohr, Pauli, and Heisenberg.

Rabi was particularly struck by a new result called the Stern-Gerlach experiment. It was already known that certain particles, such as electrons and molecules, had magnetic moments: like tiny bar magnets, they had north and south poles. In the Stern-Gerlach experiment, a beam of such particles is passed through a strong magnetic field. You'd expect particles imitating tiny bar magnets to spread out as they are deflected through a magnetic field: ones with their north pole pointing straight up to go up, ones with their poles pointing down to go down, and those with their pole pointing various degrees of sideways to go various shades of sideways, hitting the backboard in a smear. But they don't. They move only up and down. To a physicist, that's a startling result. It's as if, having discovered that particles can act like clocks, you then discover that they always tell you it's 6:00 or 12:00.

Running the beam of particles through a second magnetic field produces even stranger effects. It turns out that particles do have a magnetic moment, but it comes only in a limited set of magnitudes and directions. It is quantized. It is *quantum*. Rabi joined research on particle beams.

Stern and his team had been using non-uniform magnetic fields to study subtle effects. Rabi came up with a different approach, using a uniform field and setting the beam at a glancing angle, so the atoms would be deflected like light through a prism. It was a cleaner experimental setup, easier to use, and more accurate. This would become Rabi's signature: reinventing experiments to be clean and clever, seeking insights that brought him, he wrote, "nearer to God."

"You're wrestling with a champ," he would tell his physics students. "You're trying to find out how God made the world, just like Jacob wrestling with the angel."



Isidor Rabi, with his molecular beam apparatus

Credit: AIP Emilio Segrè Visual Archives, Physics Today Collection
Person(s): Rabi, I. I. (Isidor Isaac), 1898-1988

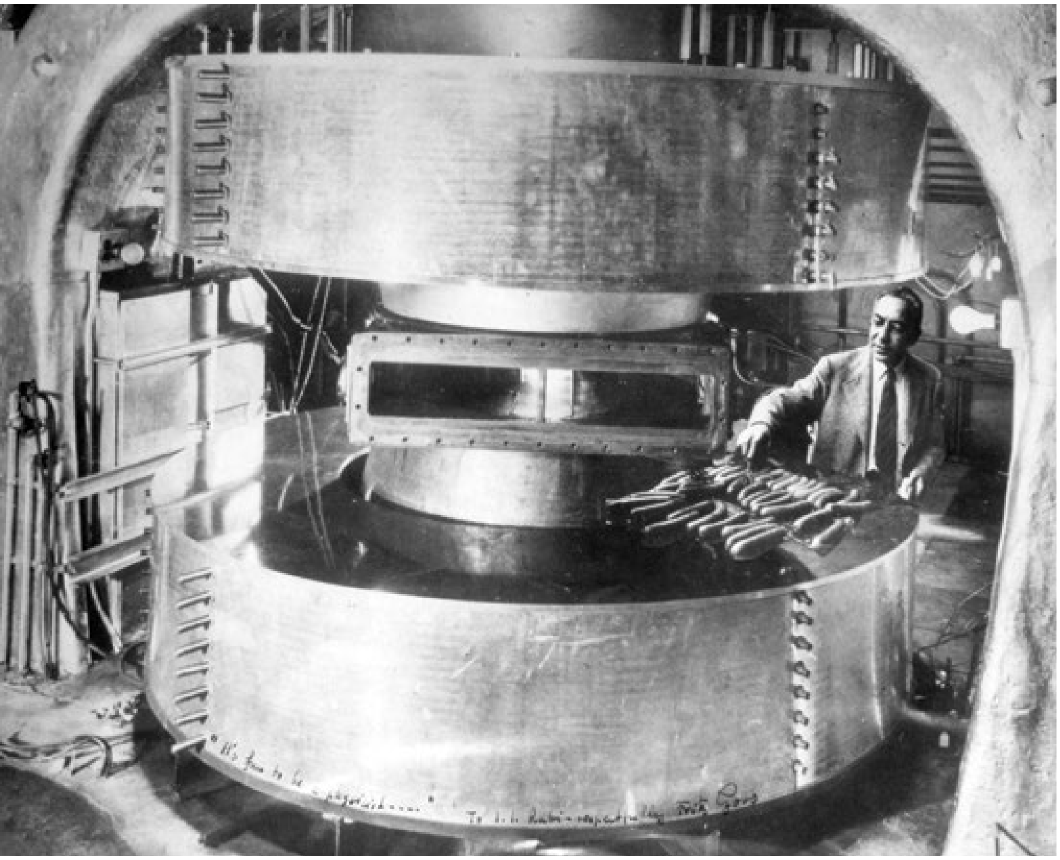
Rabi returned to New York and established a molecular beam lab at Columbia University, mapping the new property of quantized magnetic moment, also known as "spin." He spent the 1930s improving his technique. In 1937, he added something new to his setup: not just a magnetic field, but a pulse of radio waves. He predicted that the atomic nuclei would absorb this pulse and flip their spin. When their spin flipped back they would re-emit the pulse – a signal the experimenters could detect. What is more, different kinds of materials absorbed and re-emitted pulses at different frequencies. By detecting these different frequencies, scientists could distinguish between materials – even within solids.

It's called nuclear magnetic resonance, or NMR, and it won Rabi the 1944 Nobel Prize. It's the grandmother of technologies such as the atomic clocks used in modern guidance systems, NMR spectroscopy for material science and oil and gas exploration, and – of course – MRI scans.

Despite a life spent wrestling with angels, Rabi was no saint: he didn't believe women could be physicists and never took a female student; he was a great mentor but a terrible teacher.

At the end of his life, Rabi developed cancer and went for an MRI scan. The machine had a mirrored inner surface. "I saw myself in that machine..." he wrote. "I never thought my work would come to this."

– Erin Bow



Rabi, apparently cooking hot dogs on a cyclotron

Credit: Fritz Goro, courtesy AIP Emilio Segrè Visual Archives

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Perimeter continues Buchalters streak

Perimeter Institute Director Neil Turok and former Perimeter postdoc Steffen Gielen won second prize in the annual Buchalter Cosmology Prize for their work probing the genesis of the universe. It is the fourth win in as many years for Perimeter researchers, whose work has been honoured each year that the awards have existed.

The award recognizes Turok and Gielen's paper, "Perfect Quantum Cosmological Bounce," which grapples with an hypothesis called the "big bounce." Perimeter-affiliated researchers also took third prize: Associate Faculty member Cliff Burgess and Associate PhD student Peter Hayman shared it with three other collaborators for their paper, "Magnon Inflation: Slow Roll with Steep Potentials."

First prize went to Lasha Berezhiani of the Max Planck Institute for Physics and Justin Khoury of the University of Pennsylvania for their paper, "Theory of Dark Matter Superfluidity."

Laflamme named to Order of Canada

Raymond Laflamme, a founding Perimeter faculty member and long-time director of the Institute for Quantum Computing at the University of Waterloo, has been granted one of Canada's highest civilian honours. In December, he was appointed to the Order of Canada for his "outstanding achievements as an administrator and researcher who has advanced quantum science and technology in Canada." Laflamme was among 125 new appointments to the Order of Canada announced by Governor General Julie Payette.

Pedro Vieira wins Sackler Prize

Perimeter researcher Pedro Vieira has been awarded the prestigious Raymond and Beverly Sackler International Prize in Physics for his novel and powerful work in quantum field theory. Vieira, who holds the Clay Riddell Paul Dirac Chair at Perimeter, was named co-winner of the award for innovative work that has shed new light on the foundations of quantum field theory. He shares it with Zohar Komargodski, a Weizmann Institute of Science professor and Perimeter Visiting Fellow.

The $100,000 award from Tel Aviv University recognizes researchers under the age of 40 who have made outstanding and fundamental contributions to their fields. Previous winners of the physics prize include Juan Maldacena, Nima Arkani-Hamed, and Sara Seager.

Perimeter @ PPF

Perimeter Institute Director Neil Turok delivered the keynote address for 1,000 attendees of the Public Policy Forum Testimonial Dinner and Awards in Toronto on April 12. "Canada's welcoming, forward-looking society is a magnet for talent," he told the audience of leaders in public service, business, and academia. Turok dedicated the speech to friend and collaborator Stephen Hawking, recalling something Hawking said when visiting Canada for a research term at Perimeter: "The importance of special places and special times, where magical progress can happen, cannot be overstated."

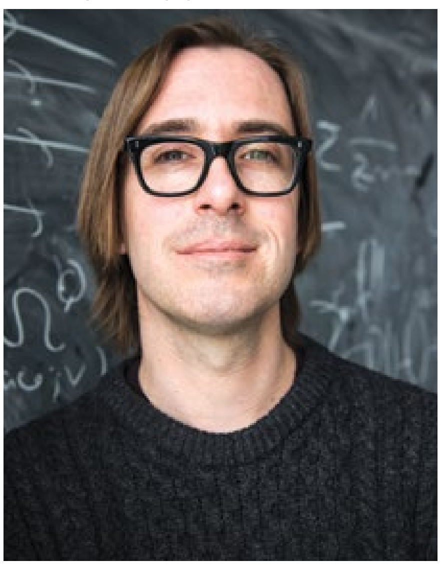
Mingling with the Minister

Canada's Minister of Science, the Honourable Kirsty Duncan, caught up with Perimeter researchers during a March visit to the Institute. The Minister shared insights on new public investments in science and education, and met with a mix of Perimeter physicists to learn about their individual research activities.

NRC @ PI: A meeting of the minds

Scientists from Canada's National Research Council recently met with physicists at Perimeter to explore mutual interests in theory and experiment across a number of fields. The two-day workshop fostered new connections and identified opportunities for possible training and research collaborations in the future.

A Royal appointment



Mathematical physicist Kevin Costello has been elected a fellow in the prestigious Royal Society of London, recognizing his pioneering research in quantum field theory. Costello joined the Perimeter faculty in 2013 as the Krembil William Rowan Hamilton Chair in Theoretical Physics, and before that was at Northwestern University. "It's a great honour to join such a venerable scientific society," he said.

WMAP team wins Breakthrough Prize

It was the experiment that marked the end of the beginning. By mapping the radiation left over from the big bang – known as the cosmic microwave background – the Wilkinson Microwave Anisotropy Probe (WMAP) brought precision to cosmology and set the stage for a deeper understanding of the universe.

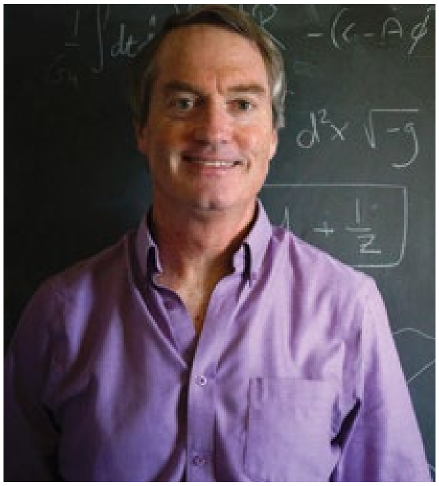
In December, the team behind that experiment won the 2018 Breakthrough Prize in Fundamental Physics, the richest prize in science. The $3 million prize was shared among the 27 team members, including Perimeter Institute cosmologist Kendrick Smith.

Perimeter Director Neil Turok said the WMAP satellite provided invaluable clues to the fundamental physics of the cosmos. "We congratulate the whole WMAP team, and our own Kendrick Smith in particular, on winning this wonderful prize. Kendrick played a key role in analyzing the data of both satellites, and continues to pioneer data analyses for CHIME, HIRAX, and other leading-edge experiments."

Connecting Canada at the AAAS

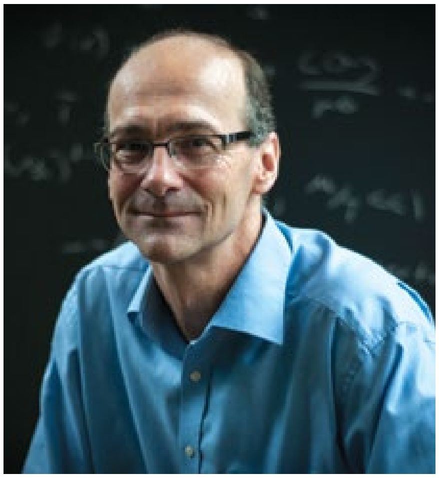
What is happening in Canadian AI research? That was one of the issues up for discussion at this year's annual meeting of the American Association for the Advancement of Science, held in Austin, Texas. Perimeter Institute Associate Faculty member Roger Melko joined CIFAR Vice President of Research John Hepburn and National Research Council Vice President for Emerging Technology Geneviève Tanguay to discuss current and promising artificial intelligence research taking place across the country.

In Memoriam



We note with sadness the passing of an old friend of Perimeter's, Joseph Polchinski of UC Santa Barbara. An eminent theorist, he made fundamental contributions to our understanding of black holes and string theory. He was one of Perimeter's earliest scientific supporters, and, as a member of the original Scientific Advisory Committee from 2001 to 2004, gave extensive input into the structure and scientific direction of the Institute in its earliest days.

Myers makes "most influential" list, again



For the fourth consecutive year, founding Perimeter Faculty member Robert Myers has been recognized as one of the world's most influential scientists on the "2017 Highly Cited Researchers" list compiled by Clarivate Analytics. Myers is the only physicist at a Canadian institution to be named to the list four years in a row.

McDonald Institute launches

Perimeter Institute is among 13 partner organizations contributing to a new national hub of astroparticle physics at Queen's University in Kingston, Ontario. The Arthur B. McDonald Canadian Astroparticle Physics Research Institute, launched in May, is a national research network dedicated to understanding some of the universe's deepest mysteries. Perimeter Faculty Chair Luis Lehner said partnering with the McDonald Institute will facilitate "collaborative research in pursuit of answers to some of the deepest mysteries in science, and mutually strengthen the training and educational outreach activities of both institutes."

Saucier + Perrotte win RAIC Gold

The firm that created Perimeter Institute's iconic building has been honoured for its legacy of inspiring architecture. Saucier + Perrotte founders Gilles Saucier and André Perrotte were awarded the 2018 Gold Medal from the Royal Architectural Institute of Canada. "The work is always innovative and interesting," wrote the selection panel. "It's timeless, consistently elegant, beautifully detailed. They integrate nature beautifully."

Power of Ideas tour comes back to Waterloo

The popular Power of Ideas tour returned to Perimeter's atrium in April for refurbishment before hitting the road again. The exhibit – which just finished a national tour during Canada's 150th as part of the Perimeter-led Innovation150 collaboration – will now be taken across Ontario for two years. By visiting schools and communities across the province, Perimeter and its partners aim to bring the magic of science and discovery to thousands more people. Visit powerofideas.ca to find out more.

Building quantum connections with the UK

Sir Peter Knight and 19 other members of the UK Quantum Delegation travelled across Canada in March to connect with their counterparts in labs, accelerators, and funding agencies. Their visit to Perimeter included a lively conversation with Director Neil Turok on the Institute's unique role for Canada and physics more globally.

How are rainbows made?

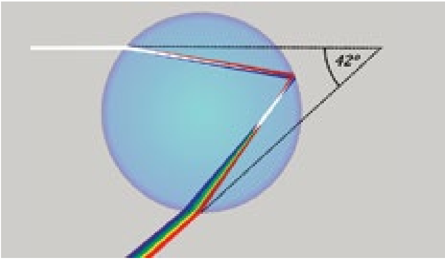
What does it look like inside a rainbow?

It's hard to forget the breathtaking beauty of a rainbow once you've seen one. The splendid arcs of dazzling colour stretching across the sky have inspired countless myths, fairy tales, poems, and songs. At Perimeter, we think rainbows (and just about everything else in the universe) only get *more* beautiful when we can understand what causes them.

The recipe for a rainbow is surprisingly simple: take some rain, add a bit of sunshine, and mix at just the right angle. To put it all together, we need to use some of the rules that govern how light behaves.

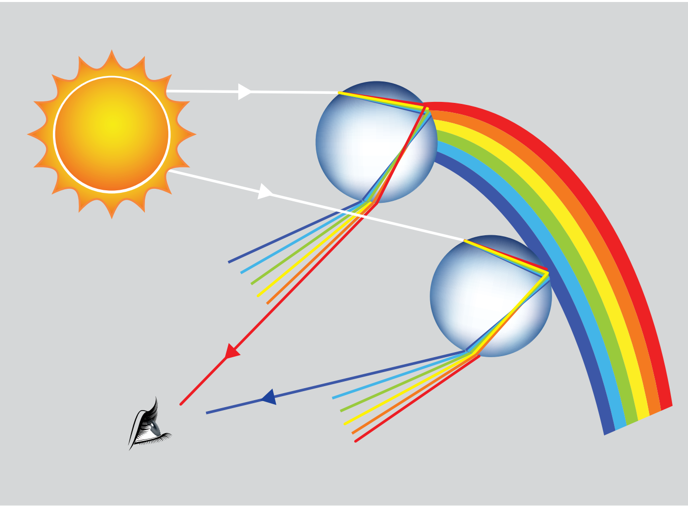
Let's start with *refraction*. When light passes from one medium to another (for example, from air to water), it changes direction slightly, or refracts. The amount of "bending" that occurs depends on the wavelength (or colour) of the light – shorter wavelengths (corresponding to bluer light) get bent more than longer ones (redder light).

Next, it's handy to know that white light isn't actually light that doesn't have colour. White (or clear) light is actually the result of blending *all* the colours of light, from red to blue, together.



White light refracts (bends) when it enters a raindrop, reflects off the back of the drop, and then refracts once more when it exits. The angle between the light that enters and the light that exits is approximately 42 degrees.

Now let's mix in the rain. When a sunbeam, containing all colours of light, enters a round raindrop, the wavelengths of light get refracted at different angles. These refracted rays then *reflect* off the back of the raindrop, and refract once more when they leave the droplet. The end result is that the white light from the sun has been spread out, or *dispersed*, into light of different colours. With enough raindrops in the sky, each one will disperse a certain wavelength of light toward a viewer's eye.



It takes many raindrops to make a rainbow. Raindrops at different positions will refract different colours of light to your eye – that's why a rainbow is red at the top and blue at the bottom. (Note: image is not to scale.)

Using optics, we know that the angle between the light that enters the droplet and the light that exits is about 42 degrees. This is why you don't see rainbows at noon, when the sun is high in the sky: the sun has to be below 42 degrees for the light to refract and reflect in the raindrops. The lower the sun is in the sky, the higher the rainbow, so you'll see the most spectacular ones at sunrise and sunset.

This angle also tells us why we get rainbows, and not rain*lines* or rain*squares*: if you map out all the points in the sky that are at just the right angle to disperse the light, you get an arc! (Well, technically, you get a circle, but half of it is blocked by the horizon.)

All of this also means that a rainbow doesn't exist in any one particular place, so you can never see inside it (or fly over it, or under it, or get to the end of one). A rainbow is essentially an optical illusion: there are no physical bands of colour in the sky – just raindrops playing with sunbeams!

– Stephanie Keating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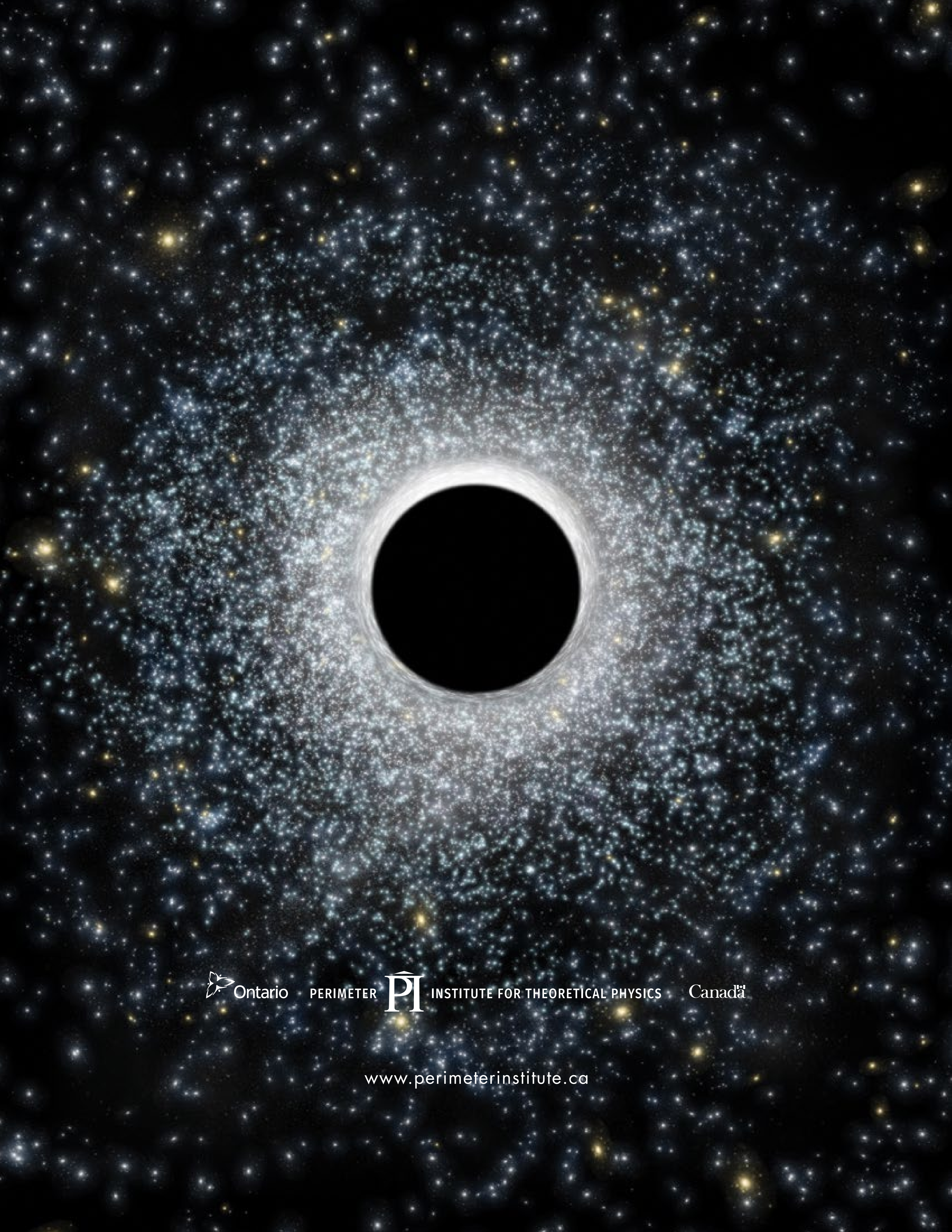

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