inside the Perimeter

fall/winter 2016/17

The Quantum Storyteller

It From Qubit

Haldane Co-Wins Nobel Prize

The Science of *Star Trek*

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

inside the Perimeter

Editor
Natasha Waxman
nwaxman@perimeterinstitute.ca

Managing Editor
Tenille Bonoguore

Contributing Authors
Tenille Bonoguore
Erin Bow
Colin Hunter
Roger Melko
Rose Simone
Neil Turok
Natasha Waxman

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

Graphic Design
Gabriela Secara

Photo Credits
Dave Chan
N. Elmehed, Nobel Media
Stephanie Keating
John Matlock
Eamon O'Flynn
Jongbum Park
Gabriela Secara

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

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

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

IN THIS ISSUE

Access to Excellence: Reconnecting Science to Society

The world has never needed scientific and technological breakthroughs more than it does today. We are faced with environmental challenges, resource crises, and economic instability. On the other hand, our scientific and technological capabilities have never been greater, and there are enormous opportunities, such as quantum technologies, on the horizon.

As the impacts of political earthquakes from Brexit to the US election start to be felt, there is a need to spread a deeper appreciation of the potential benefits of science to society. We need to find new ways of explaining and ensuring that the pursuit of knowledge enriches everyone, because that is our surest pathway to a bright future.

Perimeter Institute is fortunate to have the flexibility and agility to set an example. Our founding, governance, and funding allow us an unusual degree of freedom to define our own strategic development. This places upon us a great responsibility: to pursue leading-edge science, while maximizing the benefits both for academia and for society as a whole.

Canada's federal government is currently reviewing its entire strategy for science funding. Given Canada's many advantages – a welcoming and positive international culture, a stable, diverse society with strong public education and health systems, a small population with vast natural resources – I am convinced that, with the right choices, Canada can become a global knowledge leader. Perimeter's unique model can serve as a model of best practice which refreshes and re-energizes science, education, and their public appreciation across Canada.

Many amazing scientific institutions have been created in the past, and some have been enormously influential. The Max Planck and Fraunhofer Institutes, created after World War II, are prime examples of centres of excellence. They played a huge role in making Germany a leading scientific and industrial nation. Similarly, there is the Institute for Advanced Study (IAS) in Princeton, whose first director, Abraham Flexner, wrote a memorable piece provocatively titled "The Usefulness of Useless Knowledge" and hired, among others, John Von Neumann, who had helped lay the mathematical foundations of quantum theory. Von Neumann went on to design the world's first stored-program digital computer at the IAS. Not so useless! While Flexner's essay succeeded as a polemic, his slogan is (how shall I put it?) an inadequate justification for basic research. Likewise, the frequently used slogan "curiosity-driven" research completely fails, I believe, to capture the intensity and passion with which we pursue basic discoveries.

Perimeter was created in 1999 with an unprecedented philanthropic investment and matching government funding. Its founders wanted, above all, to create a beacon of scientific excellence which, by raising the level of aspiration and achievement in Canada, would positively impact both its local community and the whole country. Perimeter's mission was visionary: to advance our most basic understanding of nature. Theoretical physics was a brilliant choice, because it is the lowest-cost, highest-impact field in science which, in spite of its impact in transforming society over centuries, has nonetheless been relatively poorly appreciated. Typically, it has been treated as an afterthought, rather than what it is: a catalyst of great discoveries across the whole of science and technology.

In just 17 years, Perimeter has rapidly risen to prominence and is now widely regarded as a top centre for theoretical physics worldwide. How was this possible? I believe what distinguishes us can be summarized in a single catchphrase: "access to excellence."

Let me talk first about excellence which is, in many ways, the obvious part. Major advances in science are largely due to exceptional insights, due to unusual people who are willing to tackle apparently impossible problems. The search for such insights is an unforgiving activity: most new ideas are wrong, and in many ways the job of a theoretical physicist is to prove ideas wrong as quickly as possible. Rapid progress requires, first, the incessant proposal of new and testable concepts and, second, their testing both logically and through experiment. The ideal environment is one in which dogma has no place and instead there is an openness both to new ideas and to criticism.

Perimeter's is a "startup" culture that seeks to bypass the hallowed paths of heavyweight venerables like Harvard or Cambridge. Almost everything we do is different. Our small size and autonomy confers greater focus and adroitness. Our staff is likewise small but exceptionally committed, providing a highly professional and supportive environment for young scientists. We avoid division into groups or departments, encouraging collisions between different fields and approaches because it is precisely those collisions that are often the key to breakthroughs. And yes, we talk about breakthroughs as being our goal, encouraging all of us to set our sights as high as possible.

The key to our scientific success is, of course, our hiring. We look for people who are genuinely trying to do something new, difficult, and important. We look for independence, originality, and creativity, as well as technical brilliance. Often, such people are undervalued because they are not following current trends. We also look at people's qualities as team players, leaders, and mentors: are they inspired by Perimeter's vision and will they help our community achieve it? One measure of our success is that our faculty have won the New Horizons Prize of the Breakthrough Foundation, the top prize for young physicists worldwide, five times: more often than any other institution worldwide.

To recruit outstanding scientists, one must create a community which is attractive to them. This means recruiting very strong students; so, seven years ago, we created Perimeter Scholars International, now one of the top master's programs in physics which we plan to grow, with our university partners, into one of the top PhD programs globally. Bringing these brilliant young people to the Institute adds immeasurably to the energy and vitality of the science we can do here.

As fundamental as excellence is, what distinguishes Perimeter is our conviction that we must also positively connect to and impact the wider world. That is where the access comes in.

Part of access is forging strategic partnerships that can raise the quality of research and training across the country. Perimeter has partnered with nine Canadian universities on joint appointments to help them recruit outstanding faculty. A half-time position at Perimeter, with corresponding teaching relief, is a considerable draw. In addition, over a hundred theoretical physicists in Canada have been made Perimeter Affiliates, able to visit every year. If any Canadian physicist has a great idea, Perimeter is open to them spending a longer time here to develop that idea within a stimulating and supportive environment.

Technology also provides access: by making all of our seminars, lectures, and courses available online, we provide up-to-the-minute training and access to discussions and conferences at the forefront of the field. Our online archive now houses more than 10,000 talks, amassing over three-quarters of a million views in over 150 countries every year. These views count. They provide a window on leading-edge research, which is available to all who are interested around the world.

Another aspect of access is our effort to rectify physics' abysmal record in gender equity. By encouraging young women to become physicists through Perimeter's Emmy Noether Initiatives, we support young women scientists at the start of their careers. Emmy Noether Visiting Fellows visit Perimeter for extended stays to build their research and maximize their productivity.

To make the breakthrough discoveries and advances the world needs, we must enable the best minds, specially young ones, to develop wherever they are. There is an ocean of untapped talent in the developing world. By partnering with similarly-minded, spirited young institutions in Africa and Latin America – the African Institute for Mathematical Sciences and the South American Institute for Fundamental Research in particular – we are opening access to brilliant young people. Every young scientist we bring forward from a disadvantaged community will serve as a role model for thousands more. By encouraging them to enter advanced research and, in time, to contribute to the growth of excellent (and accessible!) institutions in their home continents, we can help transform the appreciation of basic science and its essential role in advancing human society around the world.

A final – and crucial – element of access to excellence is public and educational outreach, which has been a priority at Perimeter since its inception. We view it as our obligation (besides being a great pleasure) to explain what we are trying to do. Through our public lectures, festivals, online events, and publications, we are feeding and encouraging a public appetite for science.

It is specially critical that young people have opportunities to connect to science. We support physics teachers through a national physics teachers' network and state-of-the-art educational materials which are distributed across the country and worldwide. Our annual International Summer School for Young Physicists gathers high school kids from across Canada and the world and exposes them to physics' most exciting current topics.

By making our science accessible, we make ourselves relevant to society. By touring the country, as we will next year with Innovation150, and by reaching out to kids, teachers, and the public, we energize them and their interest energizes us. Kids across Canada will be motivated by their contact with Perimeter and by the knowledge that, if they are keen and work hard, they will have the chance to come to Perimeter and meet people working on the frontiers.

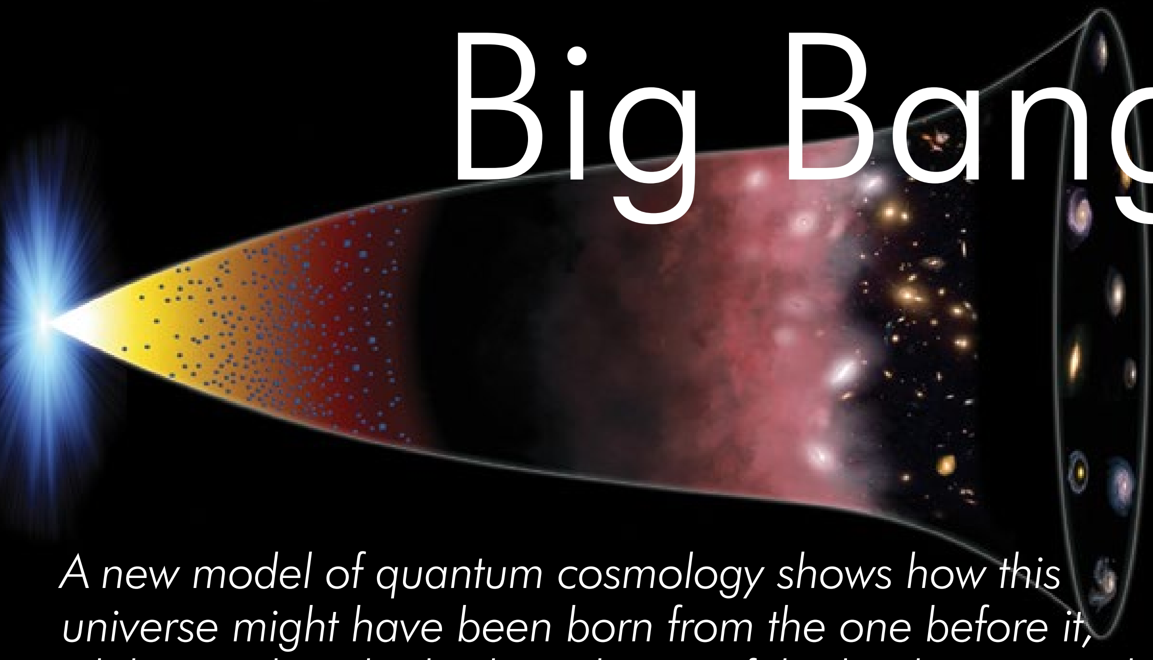
One of the greatest hazards of an advanced research centre is to become an "ivory tower," in which an aging faculty pursue increasingly abstruse ideas disconnected from reality. The kind of access we promote at Perimeter keeps all of us on our toes. We *must* be fully accountable to the public for the support we receive. More deeply, we should feel our work is for humanity, not just for ourselves. Much of the public genuinely cares about what we are doing and what we might find. We can draw energy from that support and interest: we need to live up to it by doing excellent science.

As critical as they are to the world's future, higher education and basic research currently face a number of crises. The "massification" of learning, through increased university admissions and online courses, is necessary as a means of spreading expertise and opportunity. But science, and more broadly the whole notion of "expertise," is *not* about rote learning of standardized curricula or providing more and more paper certificates. It is about asking questions, about critical thinking and pursuing deep understanding.

We need to support greater contact between scientists and, more generally, experts on the frontier of knowledge, with the broad mass of students and with the public. Perimeter's ethos of "access to excellence" offers a model for reconnecting the pursuit of basic research to the needs and aspirations of people everywhere.

– Neil Turok

Big Bang or



A new model of quantum cosmology shows how this universe might have been born from the one before it, while avoiding the broken physics of the big bang singularity.

Cosmology has a problem. The problem begins, as the universe does, with the big bang.

The standard cosmology imagines the universe's first instant as a singularity: that is, a single point, taking up no space at all, but with all the stuff of the universe inside it. As if all of reality had been divided by zero, the singularity is undefined. It has neither interior nor exterior; it cannot be described. In the face of it, the laws of physics break down entirely.

"This is a problem," says Neil Turok, cosmologist and director of Perimeter Institute. "The standard cosmology begins with an impossibility."

Working with Steffen Gielen, a former Perimeter postdoctoral researcher who is now a fellow at Imperial College London, Turok has cast a fresh eye on the universe's seemingly impossible beginning. The new research was featured as an Editor's Suggestion in *Physical Review Letters* in July.

Gielen and Turok's research imagines the big bang as a big bounce – not just the beginning of this universe, but the end of a previous universe. The predecessor universe would have contracted toward a dense state that marked its big crunch end, and our universe's big bang beginning.

But while that idea is intuitively satisfying – it at least explains where that single point of matter and energy came from – it does not by itself resolve the problems with the singularity. It is still just as impossible, just as indescribable. For all physics can predict, there be dragons.

So how did Turok and Gielen avoid the dragon(s)?

They began by looking at the behaviour of all the stuff present in the early universe. For its first 50,000 years, the universe was dominated by radiation. The matter that did exist was at very high energy, and also behaved like radiation. These materials have a special property that turns out to be crucial to this research: they are conformal.

"Conformal" has a precise technical meaning in physics and mathematics, but a shorthand translation might be "does not depend on scale." Light, for example, is conformal. Light can take the form of radio waves that are kilometres wide, or X-rays that are the width of an atomic nucleus. Maxwell's equations govern radio waves and X-rays, and make no distinction between them. This is not unique to light: particle physics strongly hints that at very high energy, all matter is likewise blind to scale.

"Our work starts from this observation," says Turok. "We make the assumption that the early universe is filled with things that have no scale. And then we try to describe a quantum universe that is filled with such material: how does it behave?"

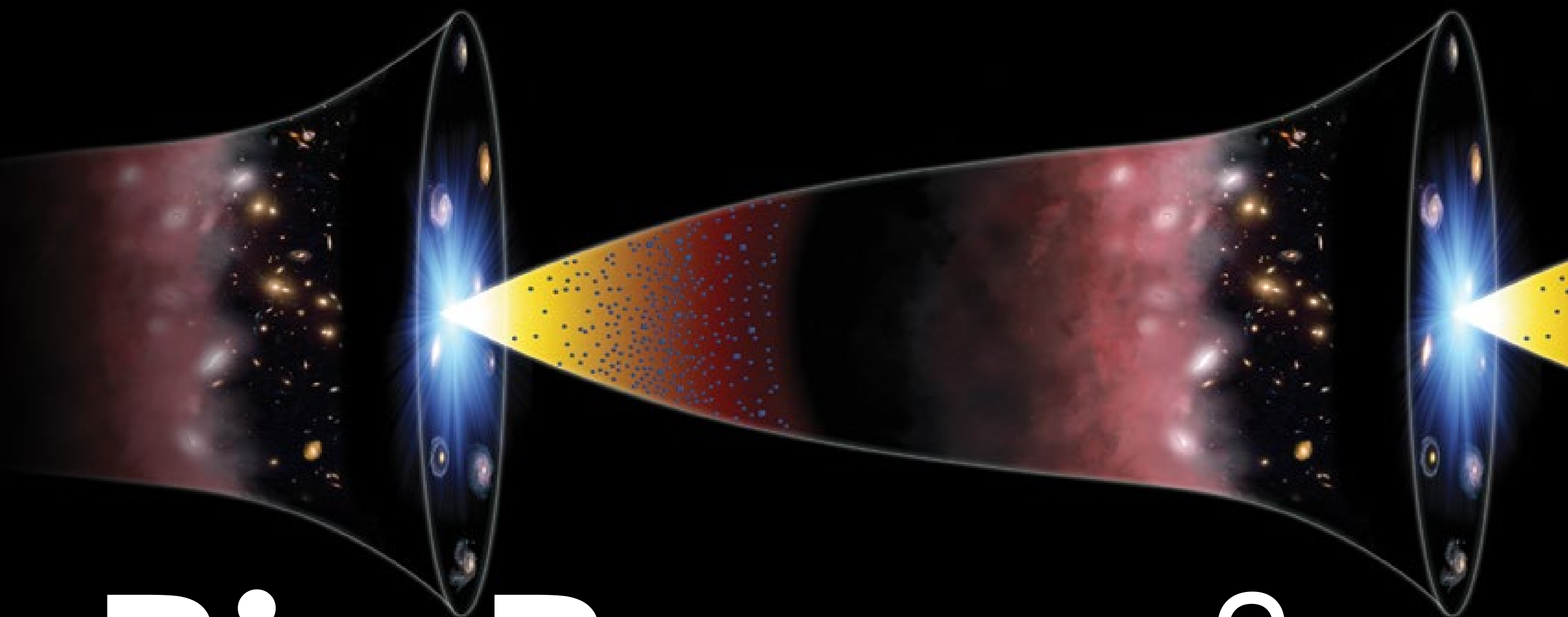
It behaves more simply than the researchers had ever dreamed. They were surprised to discover that they could use standard quantum mechanics, with no bells, whistles, or fudge factors added, to describe and predict how the universe grew. Or, winding the film the other way, how it shrinks toward the big bang singularity.

As Turok puts it: "It turns out, to our surprise, that in this very special case, where everything present in the universe is conformal, and all we are studying is the size of the universe, we could quantize the theory exactly, and work out exactly how a universe of one size transitions into a universe of another size, quantum mechanically."

Describing the growing or shrinking universe is a major accomplishment, but doesn't slay the dragon. But there, too, the researchers had an idea.

"Quantum mechanics saves us when things break down," says Gielen. "It saves electrons from falling in and destroying atoms, so maybe it could also save the early universe from such violent beginnings and endings as the big bang and big crunch."

It turns out that it could. In the model Gielen and Turok created, the universe approaches the singularity point – and then skips over it. Like a clock that avoids striking midnight by swinging its hands up and out from the clock face, the universe does this by accessing another dimension.



Big Bounce?

The "extra" dimension in question is imaginary: it is described by numbers containing the square root of negative one. The quantum universe in this model is described by complex numbers – numbers with both an imaginary and real component. At the point of the singularity, where the clock strikes midnight, it might have no real size, but could still have an imaginary size – and thus still be described by the laws of physics. So the problem of the singularity is resolved, the dragon avoided.

It seems perhaps like a cheat, but imaginary and complex numbers are everywhere in quantum physics. In this work, Turok and Gielen are using the well-established mathematics that describe quantum tunnelling: a quantum mechanical phenomenon in which a particle tunnels through a barrier that is too high for it to clear.

More than a mathematical sleight of hand, quantum tunnelling explains how fusion works in the sun, and is behind established technologies such as tunnelling electron microscopes.

Bottom line: big bounce cosmology – where one universe contracts into a big crunch until another explodes outward as a big bang – is not a new idea. Turok, in particular, has been a leading proponent of such a cyclical cosmology for more than a decade. But the sticking point has always been the moment of the bounce itself: the singularity.

This new work shows how merely assuming that everything in the early universe was conformal allows one to describe a quantum cosmology that runs the universe backward toward the singularity, smoothly over it, and out the other side. No dragons involved.

No wonder the researchers described their work as "A Perfect Bounce."

– Erin Bow

The recent detection of gravitational waves and advanced experiments such as the Event Horizon Telescope and the Planck satellite position us to learn from the cosmos more deeply than ever before.

Spectacular discoveries lie ahead, but the cosmos does not yield its secrets easily. That is why we are pleased to announce the creation of

THE CENTRE FOR THE UNIVERSE AT PERIMETER INSTITUTE.

This visionary 10-year, $25 million project has just been launched with a generous founding donation from philanthropist Carlo Fidani.

The Centre will focus on fundamental challenges in cosmology such as the big bang, black holes, dark matter, and dark energy, bringing together exceptional researchers and students, and connecting theory to experiment. It is a venture to answer humanity's oldest, deepest, and most universal questions.

Sharing Big Ideas in the Nation's Capital

Perimeter's inaugural Hill Day in Ottawa showed national leaders how fundamental physics will shape Canada's future.

It's not every day that a lively debate about the quantum nature of spacetime breaks out at Parliament Hill. But that's exactly what happened when more than 20 representatives from Perimeter Institute were hosted by the Speaker for a Hill Day in the Parliament building.

Among the many conversations about Perimeter's research, training, and educational outreach programs was one in which Greg Fergus, Member of Parliament for Hull-Aylmer, chatted with Perimeter Director Neil Turok about the origins and evolution of the universe.

Fergus, who is also Parliamentary Secretary to the Minister of Innovation, Science, and Economic Development, is a physics enthusiast who said he was "thrilled" to talk with Turok and other Perimeter scientists.

"To have a place like Perimeter Institute in Canada, bringing together the world's brightest minds, is amazing," he said. "The work that Perimeter does – and will continue to do – creates knowledge that will benefit future generations."

Turok said the Hill Day, which included Perimeter faculty, postdoctoral researchers, students, and administrative leadership, was a chance to share insights with public representative about the Institute and its connections across Canada and worldwide.

"We were thrilled to be given the opportunity to discuss Perimeter's activities with representatives and public servants across the government of Canada," said Turok. "It was a wonderful opportunity to share our plans and discuss the contributions we hope to make."

Guests included elected Members of Parliament, Senators, representatives from Innovation, Science, and Economic Development, Global Affairs, and Heritage, as well as leaders from the Natural Sciences and Engineering Research Council, the Canada Foundation for Innovation, and the Canadian Space Agency.

The gathering also previewed Innovation150, the multifaceted exhibit that will travel to communities in every province and territory during Canada's 150th celebrations in 2017.

– Colin Hunter

Members of Parliament speak with Associate Faculty member Avery Broderick and graduate student Vasudev Shyam on ideas in cosmology.

Asimina Arvanitaki (Stavros Niarchos Foundation Aristarchus Chair at Perimeter Institute) discusses Canada's role in fundamental science on the world stage.

Perimeter Director Neil Turok with the Hon. Bardish Chagger, Leader of the Government in the House of Commons, Minister of Small Business and Tourism, and Member of Parliament for Waterloo.

"The work that Perimeter does – and will continue to do – creates knowledge that will benefit future generations."

– Greg Fergus, M.P.

The Storyteller

Yakir Aharonov is a giant of quantum theory, a Socratic figure known for pinning the entire field down under one sharp idea after another. He has followed his intuition to some remarkable places: discovering the surpassingly strange Aharonov-Bohm effect, and founding the entire field of weak value measurement, for starters. "Here is an interesting answer," he's been known to tell his students. "Go find me a question."

At 83, he seems to be have been purified by time into sinew and paradigm. "You could say my life's work is finding the correct story to tell about quantum mechanics," he says. Ask him now if he thinks he has found that story, and he answers simply: "Yes."

Aharonov, who is a Perimeter Distinguished Visiting Research Chair and Professor at Chapman University, works mostly with young people, and often leaves the publishing to them. Not all of his best ideas make it into the scientific record. This summer, Perimeter's Lucien Hardy set out to fix that, convening a month-long program on quantum foundations. For the first three weeks, Aharonov gave long lectures every morning – without notes – to researchers from Perimeter and further afield. At the week-long conference that followed, "Concepts and Paradoxes in a Quantum Universe," he continued with a series of lectures entitled "Finally Making Sense of Quantum Mechanics." (All of the talks are available on Perimeter's website.)

It was not a topic that sat well with everyone. Bill Unruh – a University of British Columbia professor and Perimeter Distinguished Visiting Research Chair who, like Aharonov, is a giant in the field of quantum foundations – is a case in point. Ask him if we are finally making sense of quantum mechanics, and he pushes back at the premise of the question. "I have always found the claim that we do not understand quantum mechanics weird," he says. "It is not only highly successful, but physicists have no trouble applying it to new situations, and even brand new theories (except gravity) with very little trouble."

Unruh is not alone. Quantum mechanics is arguably the most successful theory in science – the most broadly applicable, the most precise, the most thoroughly tested. In the face of that, what does it mean to say that we don't understand it? For most of a century, the mantra "shut up and calculate" has been the majority opinion.

But there's a subtle shift in the wind. Aephraim Steinberg, of the University of Toronto, has done landmark experiments testing some of Aharonov's ideas. Ask him if we're finally making sense of quantum mechanics and you will still find your question questioned – but in a very different way. "'Are we finally' is a funny question," he says. "If that means we've been struggling for a century and now we're approaching the end? No, I don't believe that at all."

What he thinks instead is that the questions of how we make sense of quantum mechanics are becoming mainstream. There has always been a small group dedicated to this field of quantum foundations, but for decades it was marginal – to choose quantum foundations was seen as a good way to commit career suicide.

But things are changing. We can build and control large quantum systems now. We can use quantum metrology to measure unbelievably small shifts, such as those created by passing gravitational waves. Practical quantum computers and quantum sensors seem within reach. As we reach further and further into the quantum world, questions which once seemed abstract become increasingly pressing – and increasingly possible to answer. It's as if the scholastics who once asked how many angels could fit on the head of a pin suddenly had experimental access to the spirit realm.

At this conference, at least, "shut up and calculate" has given way to "sit down and listen," and "stand up and talk."

So what, exactly, are they talking about? What does it mean to make sense of quantum mechanics?

For almost 100 years, those studying quantum mechanics have struggled with disconnection between the quantum world – generally the world of the small – and the macroscopic world, the world of clocks and tables and cups of coffee. At the conference, wide-ranging discussion of this disconnection lit again and again on a single word: events.

Philip Pearle, professor emeritus at Hamilton College, is an expert in "quantum collapse": the transition in a quantum system from a state that exhibits superposition to a state that doesn't – that is, from the alive/dead cat in Schrödinger's unopened box to the cat after you check. He boils it down: "Something is missing from quantum mechanics: events. Events occur. Things actually happen in nature. And quantum mechanics does not describe that."

Quantum mechanics provides us with a wave function, which we can use to make predictions. It's fundamentally probabilistic. Where classical mechanics might tell you that an apple falling from a tree will definitely fall on your head, with such-and-such an energy, quantum mechanics can only tell you that an electron fired from a cathode ray tube has such-and-such a probability of hitting your head, with such-and-such a range of energies. Sometimes the probability is pretty high, and sometimes the range is pretty narrow – sometimes things are nearly known. But never, ever, are they exactly known.

This by itself can be a bit disturbing, philosophically. Quantum mechanics describes the universe with statistics and uncertainty; it rolls the dice. The door is still open – or at least ajar – to the possibility that quantum uncertainty is a limit on what we can know about nature, rather than a description of nature's own indeterminateness. But whether you think quantum uncertainty is in the nature of the particle or the eye of the beholder, you still have a deeper and more fundamental problem.

How do we move from the universe where the electron has a 95 percent chance of hitting you in the eye, to the universe where it definitely just did hit you in the eye? Those systems would be described by two different wave functions. Quantum mechanics can describe the one before, and the one after, but never the moment you go blind.

"If two quantum particles from the same situation behave differently in the future, perhaps nature is trying to tell us there was a difference between them — but that this difference is not in the past, but in the future."

"This is what's called the measurement problem," says Pearle. "Once you see something happening," he claps his hands together with a snap, "the wave function has to change. And quantum mechanics just doesn't do that."

Andrew Briggs is a professor of nanomaterials at Oxford who studies new materials that might be of use in quantum technologies. "If you have a closed quantum system, you can never talk about an event having happened," he says. "But our lives consist of events. We get up in the morning. Babies are born. Couples marry. Parents die. Events happen, and we know what we mean by events.

"There's no place for that in the quantum theory. So somehow, we've got to do something that will relate the fantastic, experimentally verified mathematical precision of the quantum theory of the very small, to the everyday experience of reality that you and I have in our lives."

But how? The experts attending the conference were only a small handful from a large and growing field, but the conference showcased a number of theories and approaches. Some of them are in direct opposition to others: they cannot all be true. There was debate aplenty, and very little certainty.

But Yakir Aharonov is certain. Or, at least, he's certain that he's discovered what uncertainty is for.

To hear Aharonov tell it, the trouble began when quantum mechanics first dropped researchers into a universe run by statistics, where one radioactive atom might decay, and yet another, exactly the same, might remain whole. "We can know everything about a system at a given time, yet we still can't predict what it will do in the future," he says. "That's crazy. That's a terrible thing. The whole idea of science is that we can give a reason for everything. And yet, suddenly, for no reason at all, these atoms behave differently.

"This made Einstein so unhappy that he coined the phrase 'God doesn't play dice.' In my research, I was guided all the time by the anguish of Einstein's statement, and I always set for myself the goal to find out, why does God play dice? There might be some reason for nature to behave in that way. My whole approach to quantum mechanics is to find out that reason."

To resolve the anguish of Einstein takes something radical. Aharonov's proposal is that information about the future comes back and affects the present. "If two quantum particles from the same situation behave differently in the future, perhaps nature is trying to tell us there was a difference between them — but that this difference is not in the past, but in the future."

Or to put it more baldly: the future affects the present.

The physicists gathered at the "Concepts and Paradoxes in a Quantum Universe" conference are skeptical, but listening. After all, it's Yakir Aharonov. "I know how it sounds," says Avshalom Elitzur, a former student and collaborator of Aharonov's who is now a quantum foundations leader in his own right. "It would shake the Earth under us. But it would not be Yakir's first earthquake."

Yakir Aharonov and longtime collaborator Sandu Popescu exchange paradoxes by the reflecting pool at Perimeter.

Pearle echoes that ambiguity. "I am not convinced," he says. "I am not qualified to assess Aharonov, but I would never dismiss him."

For Steinberg, experience tells him to pay attention to Aharonov's ideas. "I've been hearing Yakir say very similar things for a long time," says Steinberg. "The task of absorbing his brilliant insights is a difficult one. It's impossible for most of us to judge to what extent his new insights have really resolved these deep problems or not, but I'm certainly ready to say that he's invented a number of new perspectives that I firmly believe will help us understand things better."

Aharonov's statement – that the future affects the present – is new, but it builds on decades of work and enchanting hints.

"Quantum mechanics tell us that the universe is much richer than we thought," says Elitzur. He's one of the namesakes of the Elitzur-Vaidman bomb paradox, and discoverer of the quantum liar paradox. Both demonstrate that sometimes the mere possibility that particles might interact during an experiment is enough to affect the final state of the experiment – even if they did not interact. "That things that could have happened, but didn't, have a say in our universe," he says. "Even shadowy possibilities are important." It is a poet's universe.

"It turns out that the only consistent way for something to come back from the future without paradoxes is to have uncertainty."

More directly related is work on weak measurements. Almost 30 years ago, Aharonov and colleagues proposed a unique way of measuring quantum systems. Weak measurements were meant to resolve what's long been a quantum conundrum: we can't say what a particle is doing when we're not looking at it, but when we do look at it, we change its behaviour.

Weak measurements are a work-around for that dilemma, a technique for glimpsing what a particle is doing when we're not looking at it – or at least not looking at it very much. The scheme uses a measurement so weak, so noisy, that it gives very little information, but also creates very little disturbance in the particle: there is a good chance that it will keep on doing its quantum thing. The weak measurement scheme also screens out unwanted cases by preparing particles in some initial state, and throwing away data related to particles that end up in some unwanted final state: a schema of pre-selection and post-selection.

In 2011, Steinberg and colleagues used weak measurements to track the average paths of single photons passing through a double slit. The resulting plot showed a beautiful wave form, as quantum as could ever be imagined. Weak measurements are still controversial, and still mysterious, but looking at the Steinberg plot, one may reasonably feel that they have seen what particles do when we aren't looking at them; that they have looked at the particle and seen the wave.

Why does this work? This is the piece that's new. After years of research, Aharonov has developed a new description of quantum mechanics known as the two-state vector formalism. In it, any quantum system would be described not with one wave equation but with two: the familiar one evolving forward from the past, and

a new one evolving backward from the future. In the case of the well-known double-slit experiment, for example, the familiar vector describes what happens when a photon (or other quantum particle) leaves its source, while the new vector evolves backwards from the final location of the photon on the detection screen. A combination of the two vectors is needed to predict what occurs when the photon passes the slits.

Steinberg helps turn this into a story anyone can follow: “If I leave here at 8:00 and I tell you I’m hoping to get home at 10:00, that gives you more information about where my car is at the intervening times.” He’s quick to add: “That’s not the standard way we approach quantum mechanics. In the normal approach to quantum mechanics, you don’t get any more information by looking at where something lands than you had just watching where it was emitted.” But in Aharonov’s new formulation, information about where something lands – information from the future — is exactly what’s needed.

“Why does God play dice? Because it opens the possibilities for nature to behave in a new way.”

In reformulating quantum mechanics in this way, Aharonov thinks he has resolved the anguish of Einstein.

“Why does God play dice?” he says. “Because it opens the possibilities for nature to behave in a new way.”

Uncertainty, in his view, is a blessing in disguise, because it spares us from something worse: paradox.

“It’s like in the movies, like *Back to the Future*. Our intuition is that if something comes back from the future, like in a time machine, it immediately leads to terrible paradoxes – to stories about people who kill their grandfathers. It’s all paradoxes, paradoxes, paradoxes.”

But in Aharonov’s new formalism, uncertainty is the price we pay for ensuring that information coming back from the future to the present cannot create a paradox. “It turns out,” says Aharonov, “that the only consistent way for something to come back from the future without paradoxes is to have uncertainty.”

You can see the importance of uncertainty play out in the weak measurement experiments, or, in Aharonov’s own words: “If you have uncertainty, then in the present your measurement has lots of noise. So you do the experiment in the present, you recognize that there are lots of possibilities for error, so you repeat the same experiment many times. You record the results many times.

“And then you come to the future and you make some experiments in the future. You take the results of these experiments and come back to your recording of the ‘present.’ And you find something remarkable. Out of this error, suddenly a new order comes about, that you could not understand before.”

Aharonov’s two-state vector formalism does not make quantum mechanics predictive, but rather explains why it cannot be. In other words, it shows that God does play dice (which is not a new insight) and tells us why (which is). The formalism would explain why weak measurement seems to offer such impossible glimpses. And, perhaps most centrally, it smooths out the fundamental problem of events by introducing a new approach to time, in which the state of the present – the event – is described by the interaction of a wave function coming from the past, and a different wave function coming from the future.

"Time was always the most mysterious thing in nature," says Aharonov. "We experience time as a becoming – the present becomes another present becomes another present. There was no way for the old physics to explain this behaviour of time. We need a new approach to time. To begin this new approach, I reformulated quantum mechanics."

Time is not merely mysterious; it is central. As human beings, we are fundamentally storytellers: there is not a culture in the world that does not put stories at its centre. In stories, one thing happens after another, after another. In stories, the past is different from the future. In stories, we can use the word become, and we can use the word because. This is how we make sense of the world. Giving that up is hard.

"As crazy as quantum mechanics is, it still obeys basic principles of conservation," says Elitzur. "It occurs within spacetime, which surely has some quantum properties, but still must have the classical properties which enable classical physics and relativity to succeed. So it tells a story. Somewhere, sometime, one thing has led to another. As Chekov says, if you see a pistol in act one, there will be a shooting. Yakir is seeing many pistols, and he manages to follow them to the shooting. Or, sometimes the opposite: he hears a shot, and his methods are powerful enough to go back and reveal the gun or even the smoking gun."

But Aharonov is a storyteller.

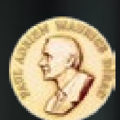
"If you like," says Aharonov, "my lifetime work is trying to find the correct story to tell about quantum mechanics, and from this, to be able to predict features in the theory, new phenomena. In finding new ways of thinking I've been able to uncover many very interesting and beautiful new phenomena."

And now, he says, he's done that. "There are still open questions about how to combine quantum mechanics with general relativity, but the main problem with how to make sense of quantum mechanics – this is the story. This is the right story."

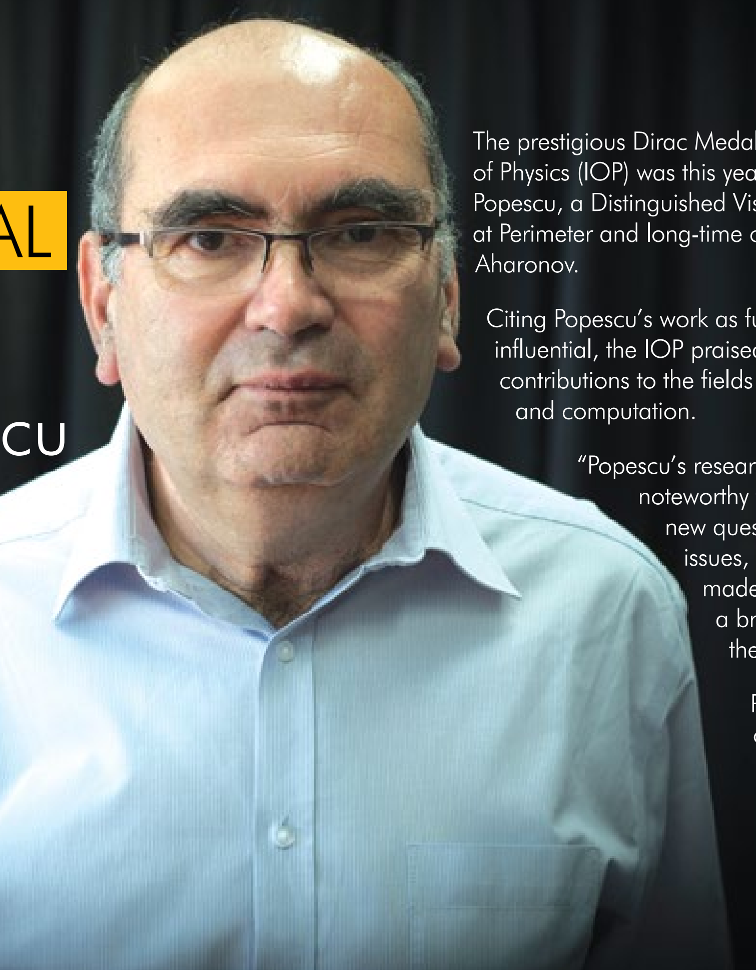
– Erin Bow

Conferences: Watch all of the talks from "Concepts and Paradoxes in a Quantum Universe" at www.pirsa.org/C16015.

Watch Aephraim Steinberg's 2013 Perimeter Public Lecture "In Praise of Weakness" at www.perimeterinstitute.ca/videos/praise-weakness.



DIRAC MEDAL goes to Sandu Popescu



The prestigious Dirac Medal from the Institute of Physics (IOP) was this year awarded to Sandu Popescu, a Distinguished Visiting Research Chair at Perimeter and long-time collaborator of Yakir Aharonov.

Citing Popescu's work as fundamental and influential, the IOP praised his seminal contributions to the fields of quantum information and computation.

"Popescu's research is particularly noteworthy for his ability to ask new questions and identify new issues, meaning that he has made deep contributions to a broad range of subjects," the IOP stated.

Popescu is a University of Bristol professor and a founding member of the Institute for Quantum Studies at Chapman University in California.

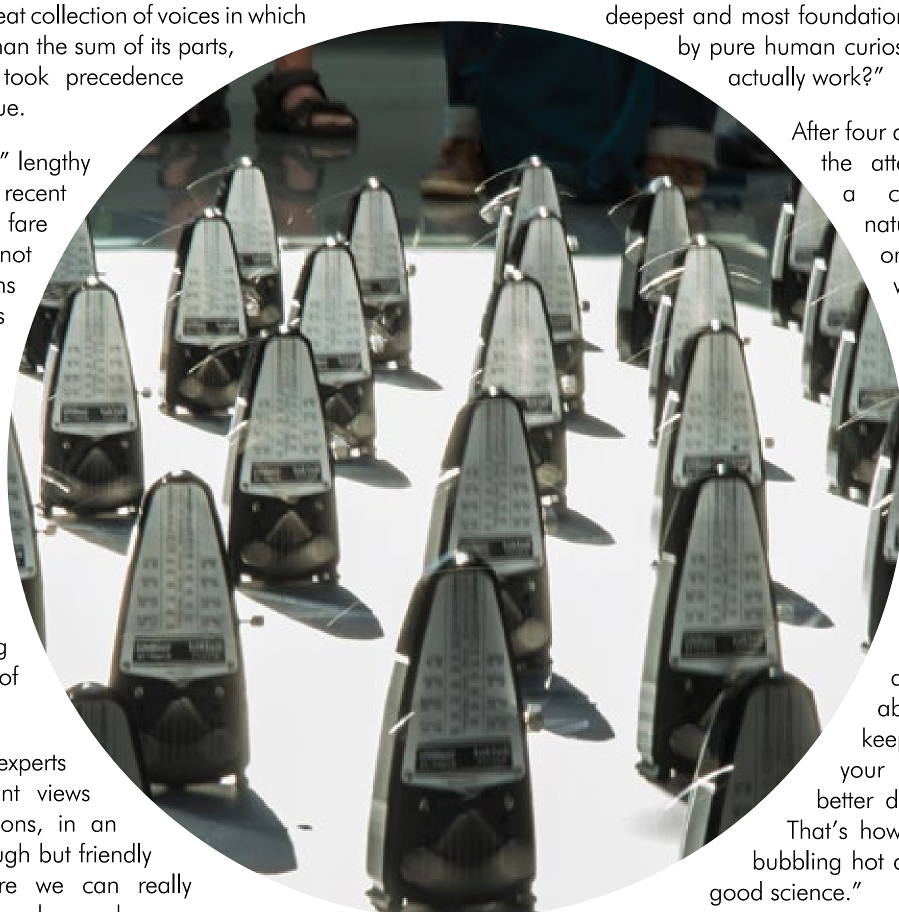
Time Is of the Essence

Scientists, philosophers, and deep thinkers from across disciplines assembled for an unconventional gathering at Perimeter.

One hundred metronomes tick-tocked in chaotic chorus, some emitting a staccato rat-a-tat, others plodding a dirge. Collectively, they tapped out a polyrhythm that filled Perimeter's atrium.

The performance of "Poême Symphonique," György Ligeti's 1962 composition for 100 metronomes, was a fitting interlude at Perimeter's "Time in Cosmology" conference in June, where dozens of leading minds had gathered from fields including physics, philosophy, biology, and more.

It was a deliberately offbeat collection of voices in which the whole was greater than the sum of its parts, where lively dialogue took precedence over scholarly monologue.



At "Time in Cosmology," lengthy presentations about recent research (the standard fare at conferences) were not welcome. Big questions were posed, answers were suggested and challenged, convivial debates were sparked.

For Lee Smolin, a Perimeter founding faculty member and co-organizer of the conference, the point was to spark new ways of thinking by eschewing the traditional ways of meeting.

"We brought together experts who have very different views to debate these questions, in an atmosphere which is tough but friendly and constructive, where we can really confront different views and may change some minds, maybe make progress on these tough questions."

Indeed, the questions were so tough that they've been examined, in one form or another, for millennia. Why does time seem to only move forward? Is time fundamental to the world, or inessential?

The questions transcend any single academic discipline, necessitating the diverse group of attendees.

"Every participant was carefully selected because we thought they would have a different point of view, offer something new," said Marina Cortês, a cosmologist at the University of Edinburgh and co-organizer of the conference. "There are so many new, diverse opinions popping up all the time, it's so beautiful. It's a format of conference that I hope will be followed and replicated."

For Sean Carroll, a professor of physics at the California Institute of Technology, the conference illustrated that, despite vastly different academic approaches to the question of time, common threads emerge.

"I've always been one who thought the interaction between philosophy and physics is absolutely crucial," said Carroll. "The things we care about – the philosophers, the physicists – are the deepest and most foundational questions. It's driven by pure human curiosity: how does the world actually work?"

After four days of lively discussions, the attendees did not reach a consensus about the nature of time, but no one was expecting that would happen. What did happen was that participants left with new ideas, new doubts, new collaborators, new challenges.

"And that's what science is about," said Carlo Rovelli, a pioneer of loop quantum gravity. "It's about doubt; it's not about certainty. If you keep doubting, you revise your ideas, and you get a better description of the world. That's how science works – it's a bubbling hot discussion that produces good science."

In that sense, Rovelli said, the symphony of metronomes was perfectly suited to the occasion.

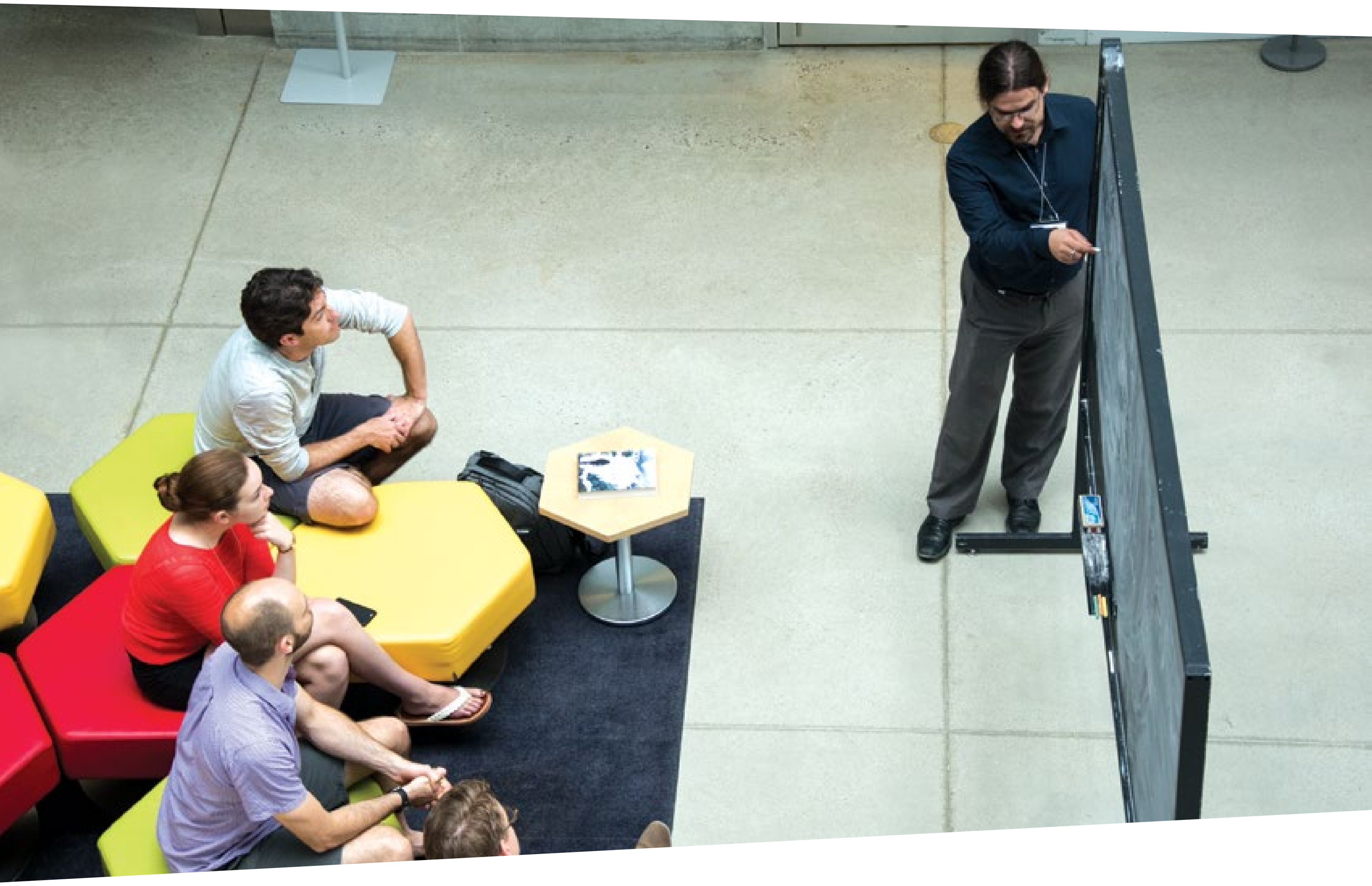
"One has to listen carefully and see how sounds keep changing, changing, changing until the end," he said. "You hear all these sounds – sometimes strange sounds – happening together. And that's where it gets interesting."

– Colin Hunter

Conferences: *Watch all the talks from "Time in Cosmology" at www.pirsa.org/C16016.*

Quantum Machine Learning

*Quantum science could not only gain from machine learning techniques, it could be reshaped by them, writes Perimeter Associate Faculty member **Roger Melko**.*



At some point in time between the rapid jump in facial recognition abilities of my iPhone and the Google DeepMind defeat of world champion Lee Se-dol in the ancient game of Go, I began paying attention to developments in artificial intelligence.

Both of these achievements occurred years ahead of predictions by computer scientists who are familiar with the extraordinary challenges posed by machine learning.

Pictures of faces are packed with a huge amount of complex information – information that is changing over time, and involves different lighting conditions, image quality, and camera angles. The extraction of a simple quantitative feature (e.g., my name) from a database of photos seems like a Herculean task.

The game of Go is another complex challenge. Each move presents a vast number of strategic advantages and disadvantages. It was long assumed that such decisions are best made by an intuitive human, evolved by nature to be adept at the abstract arts of pattern matching, imperfect prediction, and hunches.

But as Se-dol discovered when he was beaten 4-1 by the AlphaGo artificial intelligence (AI), a new breed of computer algorithms is beginning to dominate these and similar tasks.

These algorithms can be loosely categorized as "machine learning," as opposed to "machine being explicitly told what to do by a programmer." Instead of hard-coding which "features" in a photo are important, programmers have started to teach machines how to work that out themselves. Much like the old adage "if you teach a man to fish…," if you teach a computer how to auto-encode features in a photograph, it will feed you images of fish for life.

This is a massive shift in paradigm, and it could prove fruitful for theoretical physics in more ways than one.

I am a researcher in computational quantum many-body physics, studying matter, materials, and artificial quantum systems. Complex problems are our milieu. Indeed, condensed matter physics contains the most complex object in all of nature: the quantum wavefunction of a many-particle system.

If I wanted to use a computer to mathematically represent the electron wavefunction for a minuscule, nanometre-sized chunk of dust, it would require a hard drive containing more magnetic bits than there are atoms in the universe. To get around this, physicists have a grab-bag of tricks that allow us to extract the useful properties of some wavefunctions, using only the modest computer hardware currently available.

Yet many other important problems in quantum physics are veiled behind a dark cloak of infinite complexity. I began to wonder: what if machine learning could be harnessed to make a dent in this complexity? Overcoming the impasse in even a small area of research could produce unknown breakthroughs.

In late 2015, I excitedly delved into the exploding field of machine learning research. In this world of unfamiliar conferences, codes, and academic literature, I found a field complete with its own quirks, fashions, and trends – yet solidly grounded in the real-world success of what it is creating.

My first surprise should not have been one at all: physicists have long been exploring crossovers between machine learning and quantum mechanics.

However, unlike my desire to use existing machine learning algorithms and computer hardware to tackle difficult quantum physics problems, many early adopters from physics set their eyes on a different prize: translating machine learning algorithms for use on a quantum computer.

What better way to precipitate rapid advances in all facets of AI than to marry a disruptive software technology (machine learning) to a potentially disruptive hardware technology (quantum computers)? This is an appealing idea – but there are substantial hurdles in the way.

Quantum hardware offers speed-ups only for very specialized tasks. There are no concrete proposals for, say, a quantum neural network or a quantum deep learner – only bits and pieces of various algorithmic ideas.

And even if these building blocks could lead to a real-world improvement in machine learning speed or quality, the quantum hardware simply does not exist to make it a reality. We have not even fully agreed on a construction material for the qubits that could be used to produce quantum computers at an industrial scale. Decades of scientific and engineering dead ends, innovations, and breakthroughs are destined to intervene between now and development of an artificial quantum brain.

Nonetheless, today's research landscape offers remarkable opportunities. There's no denying that machine learning technology works; proof of that is only a smartphone away. But can quantum physicists harness this technology, and maybe even contribute to it?

That was the driving question behind the "Quantum Machine Learning" conference at Perimeter in August, organized by myself and some friends who also wanted to explore the potential of machine learning in quantum research.

It turns out we were far from alone. The depth of interest and breadth of perspective from both academia and industry surprised us. Close to 100 people came, from universities; information-industry giants like Microsoft, Google, and Intel; Silicon Valley startups; and government research interests from the United States. It was a heady week spent comparing research, exploring common ground, and defining what we hope will become a richly rewarding field.

Perhaps quantum machine learning could apply face-recognition protocols to quantum physics. One of the many tantalizing examples proposed by students and postdocs was to have state-of-the-art neural networks (running on conventional hardware) identify the subtle signatures of a phase of matter, using the imperfect snapshots of the wavefunction.

Since we know how to simulate these fleeting snapshots on our banks of massive supercomputers, we can program open-source machine learning code from Google and others, and use it to identify the "face" of a superconductor, or an insulator, or even an exotic topological phase of matter. In essence, we could create "Phasebook" software.

Once in place, we could then reverse the software in order to generate unique, machine-learned "mugshots" of new materials or phases. We could even use such a technology to analyze the wavefunctions of artificial quantum devices, simulated on our (classical) supercomputers as prototype quantum computers.

While most early adopters in the physics community saw machine learning as something to do *with* a quantum computer, it could first help us actually *design* a quantum computer.

We live in a remarkable time. Some physicists hope that the current revolution in AI research may unearth a rare algorithmic gem that could serve useful to quantum research. Even a small improvement in the understanding of a particular wavefunction could crack a problem wide open. In condensed matter physics, the stakes are as high as the design of a room-temperature superconductor or a new, exotic replacement for silicon.

But regardless of whether or not we make such an algorithmic discovery, this path of enquiry is rich with potential.

As physicists, computer scientists, and AI researchers, we're still looking for what unifies us. But by the end of the conference, it felt like we were forging the beginning of a community. By learning each other's language, and listening to ideas tangential to our own areas, we are creating space for remarkable crossovers, and laying groundwork for game-changing discoveries.

Perhaps the most exciting thing about the new field is that it will be driven by people much younger than me, who – unencumbered by the current, largely artificial barriers between the old fields – will forge a new path where quantum machine learning will flourish.

Roger Melko is the Canada Research Chair (Tier 2) in Computational Quantum Many-Body Physics. He is an Associate Professor at the University of Waterloo and an Associate Faculty member at Perimeter Institute.

Conferences: *Watch all the talks from "Quantum Machine Learning" at www.pirsa.org/C16017.*

Lost (and Found) in Translation

Physicists are breaking down communication barriers between specialties, and hoping to make big discoveries along the way.

How do you express an idea? Poets use words, dancers use movement, and physicists rely on a mix of mathematics and specific terminology to give form to the ephemeral.

As knowledge builds, so too does the language that encodes that knowledge. Specialization creates communities with their own dialects and tools. When a physicist steps from their area of expertise and into another, they can easily get lost in a thicket of unfamiliar terms and descriptions.

Yet there is mounting evidence that some of today's most promising avenues of inquiry in physics lie not within specialties, but between them. Of particular interest: the area between high energy physics and quantum information.

On the surface, these areas appear disparate. High energy physics aims to understand the fundamental building blocks of our physical universe at the smallest scales; quantum information science seeks to harness the weirdness of quantum theory to develop new systems for ultra-fast computation and ultra-secure communications.

In recent years, there have been tantalizing hints of connection: high energy theorists have been borrowing techniques and concepts originally developed in quantum information to make headway with some of their deepest puzzles, such as the conundrums of quantum gravity.

A year ago, aiming to promote communication and connection between the two research communities, scientists from around the world formed the It from Qubit Simons Collaboration on Quantum Fields, Gravity, and Information.

In July 2016, Perimeter Institute held the first major conference of that collaboration.

A combined workshop-and-summer-school, "It from Qubit" brought together 180 researchers from around the world – many more than the organizers originally expected, yet still far fewer than the number who actually applied to attend. Livestreams of the main lectures and research seminars enabled remote participation to meet the demand (recordings will remain available online).

The final mix was a great snapshot of modern physics, blending a broad mix of specialties: quantum gravity, particle theory, condensed matter physics, quantum foundations, quantum information, and computer science.

"It's really exciting to see ideas that were originally formulated for completely different reasons having resonance and utility," said Patrick Hayden, a quantum information theorist from Stanford University, Perimeter Distinguished Visiting Research Chair (DVRC), and director of the It from Qubit collaboration.

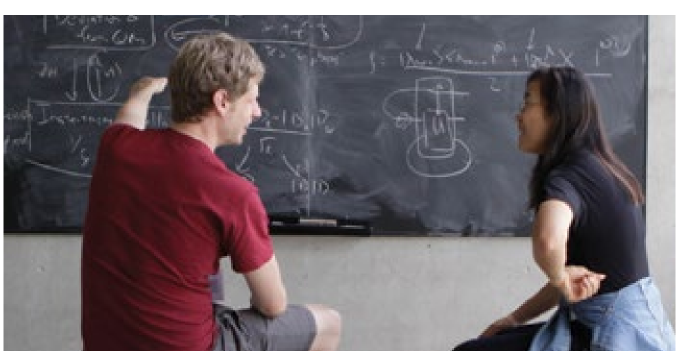
"It gives you a new perspective on your own field. Things that you thought were routine and uninteresting from a different perspective become much more profound, while things that you thought were crucially important recede a little bit into the background."

Participants set their sights on big issues: Does spacetime emerge from entanglement? How can quantum mechanics and gravity be unified? Can the new applications for quantum information uncover something fundamental about information itself?

The program started with introductory lectures and deepened towards more advanced topics, while also featuring discussions, seminars, and problem-solving sessions. Graduate students found themselves working alongside world-leading researchers as they all dived into unfamiliar waters.

"I'm here to learn," said Dorit Aharonov, a quantum computation researcher from the Hebrew University of Jerusalem who spent hours in conversation with a broad mix of attendees.

"I've always wanted to understand these deep questions about gravity and black holes, and why quantum does not meet well with gravity. For me, this is an opportunity to learn about those things in my language."



This is no small thing. Accurate translation does not just transpose *these* words for *those*. It deftly carts knowledge across the divide, allowing for it to be understood and applied in new ways.

Aharonov, like many attendees, said she expected to pursue new collaborations and research stemming from the gathering. That is exactly the result organizers were hoping for.

"There's an overlay of the old questions, the old language, and these new ideas. It just seems remarkable how well they fit together," said Robert Myers, a string theorist at Perimeter Institute who took the lead in organizing the event.

"The questions that I may be asking are old to me, but they may be completely new questions to someone else, and so they're being challenged in new ways. The enthusiasm and energy of the participants was amazing. There was a really remarkable buzz throughout the entire two weeks."

One of the goals of the summer school – and of the broader collaboration itself – is to train a new generation of researchers to be fluent in both quantum information science and high energy physics.

It's not a token effort; much of the progress in the field is being pushed by junior researchers, said Ted Jacobson, a gravitational theory researcher, professor at the University of Maryland, and DVRC.

"Of the 10 people that are producing the most interesting new ideas right now, sparking the field, probably eight of them are young people," Jacobson said.

"It's fantastic, and it gives me great hope for the field. … They have the benefit of all the hard work that came before and the revelations of string theory and AdS/CFT duality. And now they're charging forward with it and really making sense of it."

Whether or not the "It from Qubit" summer school, workshop, or broader collaboration leads to the resolution of big physics challenges is almost beside the point, said Vijay Balasubramanian, a particle physicist at the University of Pennsylvania.

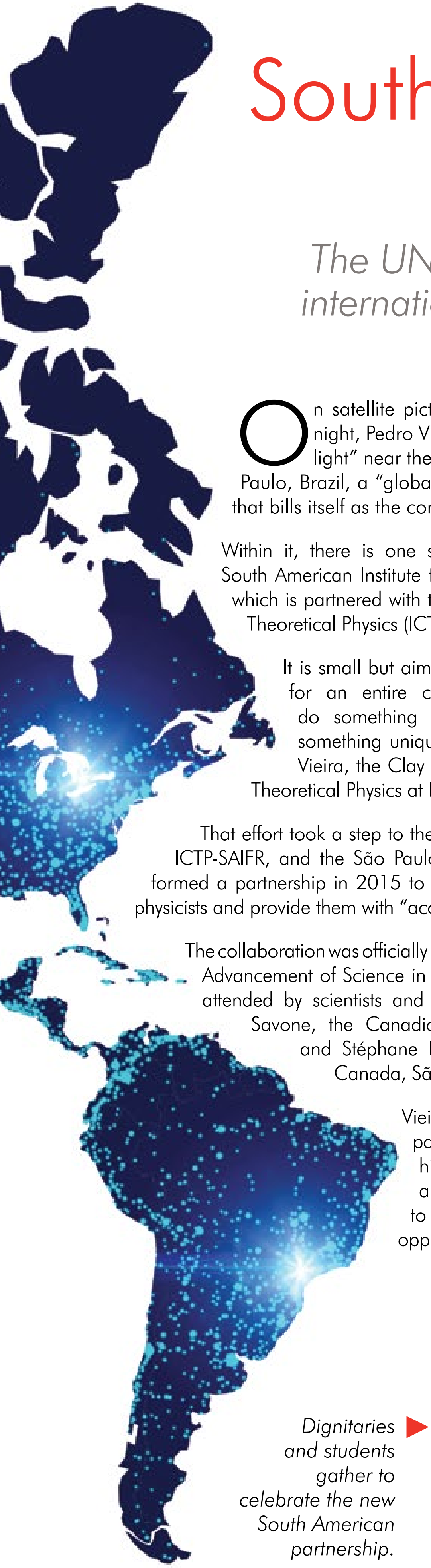
What is more important, he said, is that the young researchers flooding into the area will acquire valuable tools and techniques to dismantle the barriers of language and meaning that exist between high energy physics and quantum information.

"These are the people who are going to make the progress for tomorrow," Balasubramanian said. "I've been talking with a lot of the students, and they're completely fired up. They like this interface. 'It From Qubit' strikes a note that students find inspiring.

"And honestly, maybe spacetime is built from entanglement. Maybe it isn't. But if it isn't, the students … are going to go off and do wonderful things in other directions anyway."

– Tenille Bonoguore

Conferences: *Watch all the talks from "It from Qubit" at www.pirsa.org/C16003.*



South American Partnership Focuses on the Future

The UNESP-SAIFR-PERIMETER partnership will encourage international collaboration in theoretical physics research, training, and educational outreach.

On satellite pictures of South America at night, Pedro Vieira points to the "bowl of light" near the eastern coast. That is São Paulo, Brazil, a "global alpha city" of 20 million that bills itself as the continent's scientific capital.

Within it, there is one special point of light: the South American Institute for Fundamental Research, which is partnered with the International Centre for Theoretical Physics (ICTP-SAIFR).

It is small but aims to be a scientific beacon for an entire continent. "It is trying to do something original, trying to create something unique in South America," says Vieira, the Clay Riddell Paul Dirac Chair in Theoretical Physics at Perimeter Institute.

That effort took a step to the next level when Perimeter, ICTP-SAIFR, and the São Paulo State University (UNESP) formed a partnership in 2015 to support exceptional young physicists and provide them with "access to excellence."

The collaboration was officially celebrated during the recent Advancement of Science in South America symposium attended by scientists and dignitaries, including Rick Savone, the Canadian Ambassador to Brazil, and Stéphane Larue, Consul General of Canada, São Paulo, Brazil.

Vieira is a central player in the partnership, and will divide his time between Perimeter and ICTP-SAIFR in order to maximize collaboration opportunities.

"Brilliant young people are the lifeblood of this basic field of scientific research, where one breakthrough can literally change the world," said Perimeter Director Neil Turok.

"The values that drive Perimeter's success – the pursuit of ambitious research goals and the promotion of access to excellence for all – align closely with those of SAIFR at UNESP. We see this as an exceptional opportunity to work together and catalyze rising talent throughout South America while increasing scientific interaction between Canada and the continent."

The UNESP-SAIFR-PERIMETER partnership will encourage:

- Training programs for emerging talent at the graduate and postdoctoral levels in South America, including special schools and workshops held in Brazil
- Opportunities for talented students to attend the Perimeter Scholars International master's program
- Educational outreach to middle and secondary schools in South America, and training for teachers in the use of Perimeter Institute in-class resources throughout school systems
- Events for the broader public on the power and wonder of science
- Research exchanges and joint scientific conferences between the two institutes

ICTP-SAIFR Director Nathan Berkovits said Perimeter's global perspective made it an ideal partner for such an ambitious project.

"Our first joint activities are already showing impact, and there is no limit to what we can achieve together to support the work of talented young scientists," he said.

Dignitaries and students gather to celebrate the new South American partnership.

Drawn to Science

Jayne Reich is an artist surrounded by science. Married to physicist Jeff Tollaksen, Director of the Institute for Quantum Studies at Chapman University, she has been in the quantum foundations branch of the physics family for decades. She has thought deeply about art, the creative process, and the beguilingly strange ideas of the quantum world, which seem to require the same kind of counter-intuition that can produce great art.

When Reich accompanied her husband to Perimeter in the summer to attend a program on quantum foundations anchored around the work of Yakir Aharonov (see page 10), she decided to embark on a singular project at the intersection of art and science.

She set up an impromptu studio in Perimeter's Reflecting Lounge and invited all the scientists in attendance to sit for portraits – executed in chalk on black paper that mimicked chalkboards, the universal medium of creativity in theoretical physics. Each subject chose their own colour of chalk. As she drew, she drew her sitters out, discussing where they get their ideas, the experience of sitting for her, and whatever quantum tales they were willing to share. At the end, each was invited to add a significant equation or signature to the piece, making it a joint creation.

"The vast majority have never sat for a portrait," she said. "It's totally a new experience for them. Each one was completely unique, as every single person had a different experience. I'm in this polarized state with them, because I have a passion for discovery, creativity, finding new information."

Sandu Popescu, Perimeter Distinguished Visiting Research Chair and Professor of Physics at the University of Bristol, described the experience as mesmerizing: "Working on a large sheet of black paper – real life size – she did amazing gymnastics: large arm movements to (presumably, since I couldn't see the drawing from my position) draw long lines from the top of the page to the bottom; small hand moves for detail; bending down, stepping back, coming close, going far."

Popescu, like the other subjects, was delighted with the results. "Like every great artist, she doesn't copy reality, but interprets it," he said. "I feel she really captured some of what makes me 'me.' I just love it."

At the final dinner of the month-long program, the resulting 44 portraits were hung around the large dining room for an exhibition that lasted exactly one night.

As the mellow light of a summer evening shone through the paper, the portraits became stained glass windows, their mathematical-psychedelic vibe seeming entirely appropriate to a crowd well used to contemplating the glimmery paradoxes of the quantum.

– Natasha Waxman

Justin Dressel

Assistant Professor of Physics,
Chapman University, USA

Creative inspiration stems from identifying and elaborating patterns. Intuition identifies possible patterns, requiring time and passionate exploration; technical investigation rejects useless patterns, requiring focus and dispassionate diligence. Their union yields discoveries.

Lucien Hardy

Faculty Member,
Perimeter Institute, Canada

Art is a powerful way of representing and thinking about reality. Then the artist and subject are part of the process. Each influences the other. Sitting for Jayne was like being part of a quantum experiment, but on the unfamiliar side of the Heisenberg cut.

Clair Dai

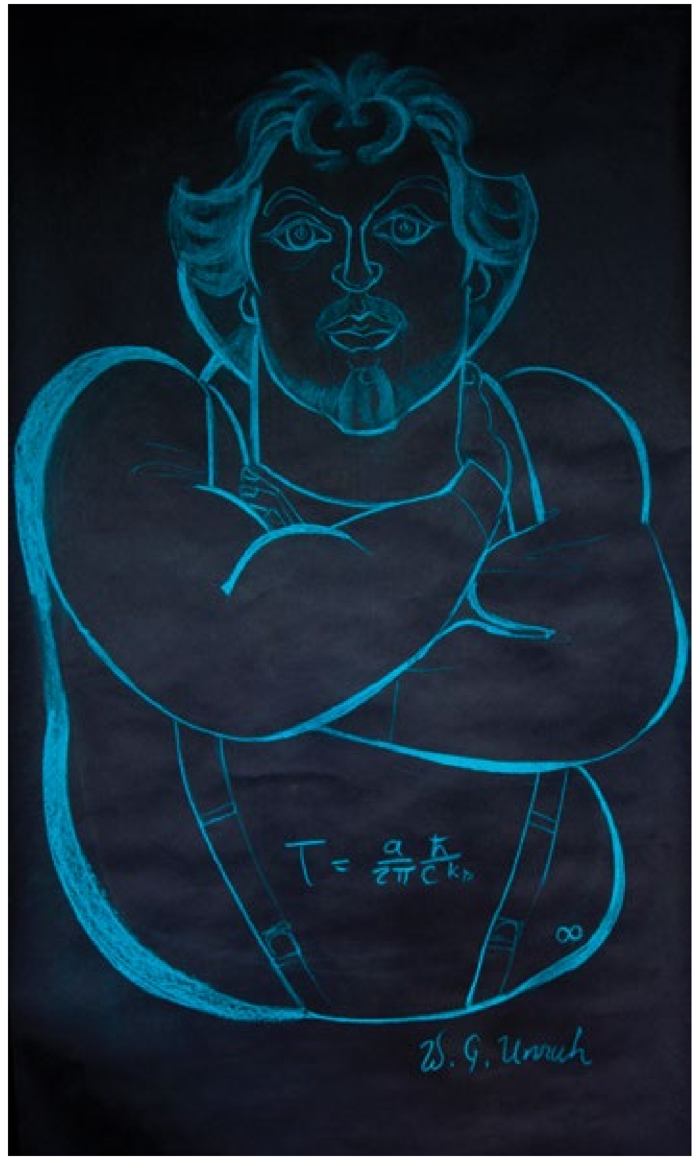
Mathematics student,
University of Waterloo, Canada

Math creation does not only relate to the intellect. A true aesthetic feeling is necessary when a mathematician wants to do some beautiful math. More specifically, one must keep all elements harmoniously in mind so that the mind can realize both totality and details without effort, to express the beauty and elegance of math.

Carlo Rovelli

Professor, Université
de la Méditerranée, France

Is there infinity between two of our fingers? How many points are there, between your index and your thumb? Can you draw an infinite number of lines? Can a painter dream an infinite number of points? I do not think so. There is no abyss going down into the small. We have only a finite number of moments. For drawing, for thinking, for counting, for dreaming.



Matt Leifer

Assistant Professor of Physics,
Chapman University, USA

Keeping still for a portrait is like a meditation, where you can either get lost in your own thought or go with the flow and lose your sense of self completely. It is a bit like my feelings about quantum theory, where the obvious need for science to describe an objective reality is in tension with the predictions of the theory, which can only describe the world from the perspective of an observer. It seems like we cannot contemplate both at the same time. We need both points of view and both states of being, and we need to reconcile them somehow. The yin-yang of the Greek letter lambda, the symbol for an objective state of reality, and rho, the symbol for a subjective state of knowledge, represent my attempts towards such a unification.

Bill Unruh

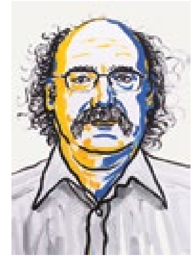
Professor, University of
British Columbia, Canada

One of the key aspects of creativity in science is to balance intense self-criticism (to make sure that you know all the holes in your ideas before anyone else does) and trying to find a way through the swamp of confusion/errors and just technical difficulties. I usually find myself redoing all calculations many, many times, since I am constantly making mistakes. But one cannot stop until one really is sure that one has it right. The equation in the portrait is the link between temperature and acceleration that I found many years ago.

To see more, go to www.insidetheperimeter.ca

Stranger Things

Perimeter DVRC Duncan Haldane shares Nobel Prize for work that laid foundation for the field of topological matter.



Perimeter was thrilled to congratulate Distinguished Visiting Research Chair Duncan Haldane on his shared Nobel Prize in Physics in October for work that helped pave the way for some of today's most promising condensed matter physics.

Although the widespread expectation was that this year's prize would go to the LIGO team, the Nobel committee instead honoured three researchers for work that unlocked a new understanding of phase transitions in matter, sparking an array of research on topological insulators, superconducting materials, and other applications.

The work began far from the world of applications, however. In the 1970s and 1980s, David Thouless (University of Washington), Michael Kosterlitz (Brown University), and Haldane (Princeton University) used concepts from a branch of mathematics called topology to explain transitions in unusual phases of matter, such as superconductors and thin magnetic films.

Their results showed that one- and two-dimensional materials can display surprising collective phenomena that make visible the quantum physics that governs all matter.

"This year's Laureates opened the door on an unknown world where matter can assume strange states," the Nobel Prize committee stated in the award citation.

The hunt is now on for new and exotic phases of matter that, many hope, could transform materials science and electronics, and even be used to build future quantum computers.

"It's wonderful to see the field of topological phases and phase transitions recognized by this year's Nobel Prize," said Perimeter Associate Faculty member Roger Melko, who holds the Canada Research Chair (Tier 2) in Computational Many-Body Physics.

"Not only is this field of physics mathematically beautiful, but topological materials hold vast technological promise, from new superconductors to the building blocks of future quantum computers. The well-deserved recognition of Thouless, Kosterlitz, and Haldane finally brings one of the most lively and exciting fields of physics into the limelight."

Topology describes properties that change in a step-by-step process. In between those steps, the system undergoes a phase transition.

In the 1970s, Thouless and Kosterlitz – then working at the University of Birmingham – used topology to create a new understanding of phase transitions, and showed that superconductivity could occur in thin layers (contrary to then-accepted theory) and at low temperatures.

That work led to discoveries in the 1980s and beyond, including Haldane's demonstration that topological concepts can be used to understand the properties of chains of small magnets found in some materials.

The work of Thouless, Kosterlitz, and Haldane showed that certain materials' properties can only be described by topological numbers, as opposed to more simple mathematical methods.

Perimeter Director Neil Turok lauded Haldane and his co-winners for their transformational work.

"Quantum mechanics produces some of its most weird and wonderful effects in systems of many particles, where the identity of the individual particles are subsumed in a collective quantum dance," said Turok.

"Duncan pioneered the mathematical description of such systems, showing how the quantum collective states probe the shape as a whole."

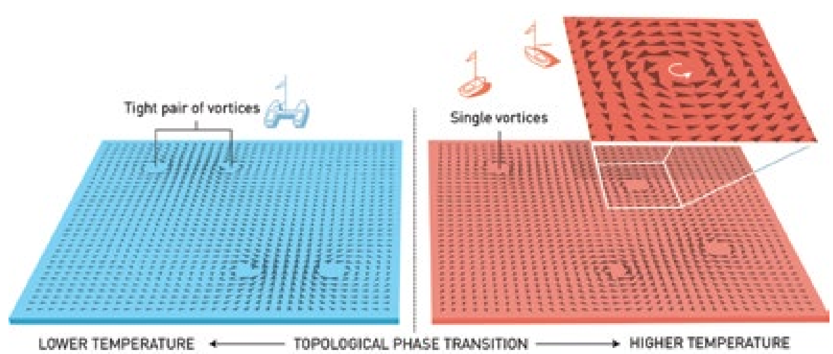
Haldane's work has always been "ahead of the curve," Turok said. "His work is always novel and surprising, but seems a little abstruse. It takes about a decade for others to fully appreciate."

That final point isn't lost on Haldane himself, as he explained to the *Wall Street Journal*: "At the time, I thought it was of scientific interest and mathematical interest, but I didn't think it would ever find a particular realization," Haldane said.

"My work was a kind of sleeper. … It didn't become such a big deal until my work got extended [by other scientists]. You never set out to discover something new. You stumble on it and you have the luck to recognize that it is something new."

– Tenille Bonoguore

Phase transition occurs when phases of matter transition between each other, such as when ice melts and becomes water. Using topology, Kosterlitz and Thouless described a topological phase transition in a thin layer of very cold matter. In the cold, vortex pairs form and then suddenly separate at the temperature of the phase transition. This was one of the 20th century's most important discoveries in the physics of condensed matter. (Credit: Nobel Prize Foundation)



Teens Encouraged to Follow Their Curiosity at Physics Summer School

Life lessons merge with science and fun at International Summer School for Young Physicists.

It was a lesson few, if any, of the 40 studious high-schoolers attending the International Summer School for Young Physicists (ISSYP) could have anticipated.

Not one, but two, of the theoretical physicists they met at Perimeter Institute had dropped out of high school, then picked up their studies later on.

"We should have planned that better!" laughed Perimeter Outreach Scientist Kelly Foyle when the second physicist fessed up. "You should really finish school, everyone!"

It was a lighthearted moment that carried a deeper message: the path to becoming a physicist isn't always straight, and you don't need to know at the start where you want to finish.

Much more important is that you are curious and willing to work hard – particularly with other people – said cosmologist Matthew Johnson, an associate professor of physics at York University and Perimeter Associate Faculty member.

"No scientist works in isolation. It's a community," he said. "The best part of my job is the people. I have a lot of fun, and I think that's extremely rare [in life]."

The students each had their reasons to attend the summer school in July: for some, it was a deep curiosity about the nature of math; for others, it was a test of their devotion to physics.

What they found was their community. They collaborated on science projects, listened to leading researchers, visited experimental sites, and goofed off at bowling.

And they got down to work, tackling a range of topics from Hawking radiation to the twin paradox.

"It's pretty challenging, but that's what makes it exciting," said 15-year-old Answesha Sahu from Tanzania. She applied to the school after meeting Perimeter Director Neil Turok in Africa, and left the Institute even more committed to her dream of becoming a cosmologist. "It makes me want to go deeper, and understand everything better."

Keynote talks included sessions with Perimeter Faculty members Lee Smolin and Robert Spekkens, and a question-and-answer session with Johnson and PhD student Lauren Hayward Sierens.

During his own keynote address, Turok encouraged the students to keep questioning the world, each other, and themselves, and to not feel discouraged by the many challenges in the world.

"We should feel optimism. The world faces big, big problems… but when you look at theoretical physics, it tells you what you need," he told the class.

"All the other problems can be solved. Of course they can. Theoretical physics is an example of what can be done when we work together and do what we're capable of."

Many of the students said they feel a pull between pursuing physics and studying other subjects they find equally compelling.

That was a particular issue for 17-year-old Maya Burhanpurkar, from Oro-Medonte in Ontario, who has already developed a strong reputation as a scientist-to-watch.

At 12, she prototyped an "intelligent antibiotic." At 13, she discovered promising novel cardio-protective properties of two experimental Alzheimer's drugs. At 14, she discovered the physical nature of a new property in Newtonian physics, becoming the first person to measure the time-integral of distance. She has worked on a near-Earth asteroid-tracking project, and plans to take this academic year off to work on a robotics project at the University of Toronto before starting at Harvard in 2017.

"My research interests are extremely diverse," she said. "I just love everything. I suspect that's going to become a problem when I have to pick my major in two years."

Like many of her ISSYP classmates, Burhanpurkar had hoped the camp would help narrow her options. Instead, it revealed just how many paths she could take.

"I think it's left me more indecisive than I was when I came in," she admitted. "In applied research, you get instant gratification, and I appreciate that – I love to code and that kind of thing – but fundamental, basic research, that's the research that leads to those colossal steps forward."

Sarah Freed from Edmonton, Alberta, also found herself swinging between possible paths now that she's finished high school.

"I am still figuring out what I want to do in university, but physics is definitely an option," she said. "Biology is another one, because that also explores the fundamentals of life."

But when it comes to ISSYP, finding answers isn't always the goal. In such a collaborative field, community is just as important. "I have met so many interesting people from so many different countries, and it has been an amazing experience," she said.

And for Matteo Rosales, who was preparing to start Grade 11 in France, the science and the summer school revived his childhood love of discovery.

"When I was little, I really liked magic, because I liked the idea of finding something different from this grey and monotonous world. I wanted answers to things that are not really tangible," he said.

"In a way, physics has the answers. Physics is not magic but it is another way to see the world."

– Tenille Bonoguore

Calling all high school physics aficionados!
Applications for the 2017 edition of ISSYP open in December, and close March 31.

www.perimeterinstitute.ca/outreach/students.

Presenting Partner:

RBC Foundation

With additional support provided by Maplesoft, Deloitte, and the Van der Veen Family.

THE MEDIUM IS THE PASSAGE

How two Perimeter researchers cracked open a door to quantum computation that has been considered closed for 10 years.

A theoretical doorway to quantum computing long considered closed has been cracked back open by two Perimeter postdoctoral researchers.

In two papers published this year in *Physical Review Letters* and *Physical Review A*, Daniel Brod and Joshua Combes, with collaborator Julio Gea-Banacloche from the University of Arkansas, revive the idea of using something called a cross-Kerr medium to create information-processing gates that would enable photons to interact – an item at the top of the wishlist for optical quantum computation.

The researchers offer a concrete example of how to construct a controlled-phase gate and hope that, by showing that the scheme is possible in principle, they will help breathe new life into a long-dormant avenue of inquiry.

The proposal to use photons for classical computing was first made, by Gerard Milburn, in 1989. Isaac Chuang and Yoshihisa Yamamoto extended the idea to quantum computing in 1995.

These proposals were based on something called a Kerr nonlinearity (in which a particular kind of medium permits photons to interact with each other, producing a phase shift) and did the analysis using light of a single frequency.

But two influential papers later blew the idea out of the water. In a 2006 paper, MIT professor Jeffrey Shapiro found that, once real-world effects were added, the original proposals fell apart. Then, in 2010, Gea-Banacloche modelled the Kerr medium at the atomic level and also found that those original proposals fell apart.

Most researchers took those two papers as a clear "no-go" sign and pursued other lines of investigation, most commonly the Knill-Laflamme-Milburn (KLM) protocol that today dominates the field of optical quantum computation.

But a smaller group kept knocking on the Kerr-medium door. For more than a decade, they made little progress. Over the years, a trend emerged: researchers would present new attempts to make the scheme work, then other researchers would take a close look and show where those attempts failed.

Now, Combes, Brod, and Gea-Banacloche have found one instance in which it does work.

*

Optical quantum computation would be much easier to create if photons were able to interact directly with each other. Instead, like shy people at a cocktail party, they move through the same space without talking to each other.

That means photon interactions need a mediator – kind of like a mutual friend passing messages between those shy folks so they can communicate without having to strike up the conversation.

Nonlinearities are the optical-quantum-computing equivalent of that beleaguered friend: the site of an information exchange. Nonlinear gates interact with the photons and essentially do the talking for them. In the case of a controlled-phase (CPHASE) gate, that interaction results in a phase shift.

Current attempts to create CPHASE gates require intense management at each step of the way: to execute complicated control pulses and sequences, to account for things like error correction.

That makes using a Kerr medium particularly inviting; in theory, the medium would do all the work without requiring intense handling at each step.

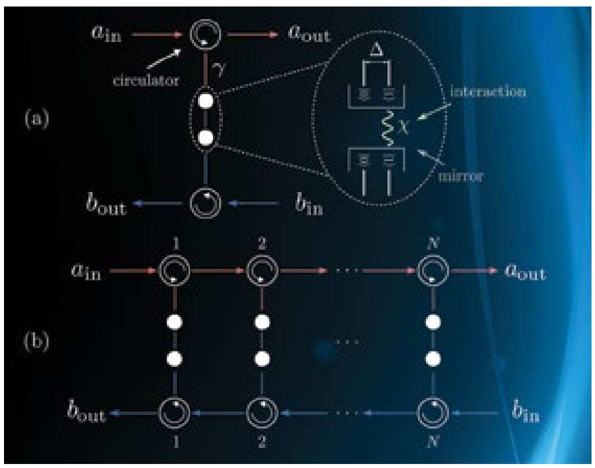
In their papers, Brod and Combes, who are from Brazil and Australia respectively, detail a passive CPHASE gate made from a two-atom Kerr medium. These pairs of atoms are used to create sites where the photons can interact, and multiple sites are chained together to form the quantum gate.

If no photons enter the gate, the atoms remain in their ground states, and no interaction occurs. When one photon enters the gate, only one of the atoms gets excited and has its electron jump to the higher-orbit excited state. The photon is spit back out with no change, and again no interaction occurs.

However, if two photons enter the gate, both atoms get excited. The electrons in the excited atoms jump to a higher orbit, where they can talk to each other. Due to this atom-atom interaction in the gate, the photons are released with a slightly different phase – without the need to manage any aspect of the interaction itself.

And their proposal can withstand real-world effects.

"It's kind of a black box – just throw your photons in there and see what comes out at the other end," says Brod. "They are very explicitly not ignoring each other anymore."



(a) The physical system inside the unit cell, consisting of two coupled two-level atoms (b) The main proposal using N interaction sites with counter-propagating photons

Why does the scheme proposed by Brod and Combes work when so many others have failed? First, they assumed a "Goldilocks" photon, which turned out to be just the right size for the computation to succeed.

Second, they allowed their photons to interact at multiple places. Each site shifts part of the photon wave packet; after a number of gates, the desired phase shift is achieved.

Third, they realized that having the two photons travel in opposite directions (counter-propagating) rather than in the same direction leads to a much greater quality gate.

This final realization came from an unexpected place. Brod had previously worked on quantum computing using random quantum walks, at the Institute for Quantum Computing at the University of Waterloo.

That research team had used counter-propagating waves to deal with spectral entanglement. As Brod puzzled over the cross-Kerr challenge, he saw a connection.

"It's in a different field and different setting, but when you abstract away the physics, it looks very similar," Brod says. "I got the intuition that there are things these guys do that optics people have never tried. Let's try that."

If the previous "no-go" papers had demarcated the places cross-Kerr nonlinearities failed, Brod and Combes targeted the gap that was left, and found a model that works.

When the pair posted a preprint of their long paper to the arXiv, Gea-Banacloche took a close look – and ended up contributing a section to the paper and becoming a co-author.

Those decade-old papers are still correct; under the assumptions made in Shapiro's and Gea-Banacloche's papers, the systems do not work. But Brod and Combes expect that – should researchers instead use the "Goldilocks" regime of these recent papers – schemes previously deemed to have failed could, in fact, work.

*

There are a number of schemes currently being pursued to harness photons for quantum computing.

The dominant KLM scheme can require thousands of gates to reach a fidelity of 95 percent. (How good a gate is – its "fidelity" – can be interpreted as how likely the gate is to work, or it can be a measure of noise in the data.)

A different cross-Kerr proposal, published in 2013, used photons going in the same direction, and required a million sites to reach 95 percent fidelity.

This new cross-Kerr proposal achieves 95 percent fidelity with just five interaction sites. Twelve sites would bring that up to 99 percent fidelity.

For purists, the impossibility of a 100-percent-fidelity CPHASE gate has been a reason not to pursue the scheme. But for Brod and Combes, that is exactly the reason CPHASE gates via cross-Kerr are worth pursuing.

General quantum computing embraces quantum error correction, which says operations don't need to be perfect – they just have to pass a threshold of quality.

These two new papers show that cross-Kerr nonlinearities can deliver what the authors believe is a similar acceptable level of imperfection. The same "good enough" principle could apply.

"People want things to be perfect, which is a lofty goal, but it's not necessary," says Combes, who did the work as a postdoctoral fellow at Perimeter and the Institute for Quantum Computing, and recently started a research fellowship in Australia.

"You're never going to get a perfect CPHASE gate, but maybe we don't actually need one."

– Tenille Bonoguore

Digging Into the Delightfully Strange

For Emmy Noether Visiting Fellow Gemma De las Cuevas, the difficult, surreal ideas of quantum mechanics are irresistible.

Of all the subjects she could have studied, Gemma De las Cuevas was drawn to quantum physics because of its strange, surreal qualities.

"Everything that has to do with quantum physics is surprising and exciting because it is so different to anything we are used to," she says. "Never mind science fiction, it is quite enough to understand quantum mechanics."

De las Cuevas is an Elise Richter fellow, a senior postdoctoral researcher in quantum information at the Institute of Theoretical Physics at the University of Innsbruck, Austria. She is also one of seven Emmy Noether Visiting Fellows who are spending time at Perimeter in the 2016/17 academic year.

Noether was an influential 20th century German mathematician whose theorems underpin much of modern physics. Through a series of Emmy Noether Initiatives, including the visiting fellowships, Perimeter is seeking to help redress the long-standing imbalance of women in physics while encouraging breakthrough discoveries.

While more women are going into physics, De las Cuevas acknowledges that there are still challenges, including the lack of role models for young women. "It is not fun, for women or for men, to have such an unbalanced situation. So I think programs such as this are a good idea."

De las Cuevas has an eclectic and curious mind, and is prone to picking up books that range from *The History of Western Philosophy* by Bertrand Russell to *The Beginning of Infinity* by David Deutsch. She loved many subjects in school, but chose physics because it offered the greatest challenges.

With its blend of difficult and surreal ideas, quantum physics proved irresistible. "It has a mixture of both understanding the world physically, and also abstract thought," she says. "[It is] a starting point for understanding the world."

Her research focuses on tensor networks, which try to describe quantum many-body systems that involve a large number of interacting particles. Understanding these systems is important to many areas of physics, such as condensed matter and quantum information.

Tensor network theory can take the many-body wave functions of a strongly correlated system, like the electrons that move tightly together in a superconductor, encode them and break them down to a series of tensor operations. This can simplify our understanding of how quantum particles behave en masse, exhibiting new emergent properties that the individual particles don't have. (Buoyancy, for example, is an emergent property of water – single water molecules don't exhibit buoyancy, but many of them together do.)

"We may understand how a few quantum objects behave and how to describe them, but the description does not work well when you scale up and try to put together many quantum objects. So we need new ideas and we need to find an emergent description," De las Cuevas explains. Just as a brain can be described at the level of neurons or in terms of psychology, so it is that in physics, "when we look at different scales, we require completely new descriptions," she adds.

Her research involves using tensor network theory to improve the understanding of mixed quantum states and continuum limits within certain classes of tensor networks. But recently, she has also been working on developments at the intersection between theoretical computer science and physics.

"I was attracted to the fact that it is a young field with close connections to experiments on the one hand, and to abstract concepts in mathematics and theoretical computer science on the other hand," De las Cuevas says.

In theoretical computer science there are "universal Turing machines," which are abstract models of computation that help investigate the limits of computation. These computational models are "universal," because with appropriate input, they can simulate the steps to compute anything that can be computed.

Earlier this year, De las Cuevas showed that something similar happens in physics. In a paper published in *Science*, "Simple Universal Models Capture all Classical Spin Physics," she and co-author Toby Cubitt showed that the physics of "classical spin models," which are simplified models of interactions between particles, is reproduced in the low-energy sector of certain universal models in physics.

Now, she is continuing to look at the similarities between these universal models for simulation in physics and universal Turing machines for computation. In theoretical computer science, there is the concept of an undecidable problem, a decision problem for which it is known to be impossible to construct a single algorithm that always leads to a correct yes-or-no answer. De las Cuevas is investigating the role of undecidability in physics.

Perimeter's Tensor Network Initiative and the diversity of its research areas were prime attractions for De las Cuevas. She recently completed a month-long visit in the fall, and plans to make several more research visits to the Institute during her year-long fellowship.

"I was really excited to be able to come here and to be able to talk to people in different fields and learn from them," she says. "I really am just working on a tiny corner of a very big theory, but I feel that I am part of a large community and team."

She says Perimeter is a "unique and special place" where she gets to meet interesting people who are thinking deeply about many questions. "For me, it is a like a place I had dreamt of, but didn't know it could exist."

– Rose Simone

Perimeter is challenging the under-representation of women in physics through its Emmy Noether Initiatives, backed by the Emmy Noether Circle of donors who champion women in science. To become a supporter, email jwatty@perimeterinstitute.ca

EMMY NOETHER
FELLOWSHIP

Emmy Noether Visiting Fellows are invited to work at Perimeter for periods of three months to one year. They pursue research and collaborate within the Institute's scientific community while on leave from their home institutions.

Applications for the 2017/18 Fellowships close on **January 10, 2017**.

For more information, please visit **www.perimeterinstitute.ca/emmy-noether-visiting-fellowships**.

To learn more about Perimeter's Emmy Noether Initiatives, go to **www.perimeterinstitute.ca/research/emmy-noether-initiatives**.

Teachers Learn to Inspire Passion for Physics

EinsteinPlus helps teachers bring modern physics concepts to life in classrooms around the world.

The boisterous chatter can be heard down the hallway from the seminar room where teachers are playing with Slinkies.

"Very nice!" someone calls out, as a spiraling wave undulates down one of the springs.

At coffee break, the room erupts in laughter as Philip Freeman, a teacher from Vancouver and the session facilitator, flaps his arms in circles, demonstrating his "gravitational wave walk."

This is EinsteinPlus, Perimeter's annual one-week intensive workshop, drawing more than 40 high school physics teachers from around the world.

It's designed to arm teachers with ideas and hands-on tools, including Perimeter's classroom resources, to spark a passion for physics in their students. The teachers are encouraged to share what they've learned with their fellow educators back home, broadening the network of teachers using the materials and resources.

This year's sessions focused on topics that have recently made headlines: the discovery of ripples in spacetime known as gravitational waves, the Nobel Prize-winning discovery from the Sudbury Neutrino Observatory (SNOLAB) that neutrinos have mass, and the anticipated discoveries from the Event Horizon Telescope, a global array set to get the first-ever images of the swirling gas and energy around a black hole.

When it comes to explaining such concepts with hands-on classroom activities, ingenuity is the name of the game. EinsteinPlus teachers have an arsenal of easy-to-find, inexpensive items at their disposal, from paper cups to Christmas ornaments.

Springs can be used to demonstrate all kinds of waves, but can also serve as an introduction to gravitational waves and how the Laser Interferometer Gravitational-wave Observatory (LIGO) discovered them. Marbles can double as neutrinos. A cardboard box with holes can represent a neutrino detector. A homemade waterfall in a plastic container can represent a black hole environment. Pop cans attached to Christmas tinsel can be used to demonstrate the photoelectric effect.

The teachers at EinsteinPlus are already physics aficionados, looking to share ideas. Yvonne Dietzenbacher, from the Netherlands, was an engineer specializing in plasma systems before becoming a high school physics teacher. But knowing physics and teaching it are two different things: Dietzenbacher says her current job, making physics fun and interesting, is far more challenging.

"I need more inspiration, and I need to find out what students find difficult and how can I make it clearer," she says.

The Netherlands is changing its physics curriculum, putting more emphasis on modern physics and recent discoveries, so learning at Perimeter, where modern physics is researched, taught, and shared at a high level, "was a great opportunity," she says.

The physics curriculum is also changing in Saskatchewan, which led to a contingent of teachers from that province attending EinsteinPlus this year. "We are taking the emphasis out of the 1600s and bringing it into the modern century," says Rory Bergermann, a teacher from Saskatoon.

Bringing physics teaching into the 21st century helps students realize that "science is not just something that is already known and fixed," adds Birgir Asgeirsson, who teaches in Reykjavik, Iceland. "It is important for them to feel that there is something for them to do, something for them to discover in the future."

Most of all, EinsteinPlus is about inspiring passion, says Simon Levesque, a teacher and facilitator from Trois-Rivières, Québec.

"I think it is important to light the fire, to ignite the passion," Levesque says. "In a sense, it is like what pianists will do with their students as they learn to play. I want them to have the skills, but I also want them to be curious. I want them to like science. That is hard work, but that is my job."

– Rose Simone

The 2015/16 EinsteinPlus program was supported by Maplesoft.

Want to attend EPlus? Applications for the 2017 program open in December, and close April 7. Find out more at www.perimeterinstitute.ca/outreach/teachers.

Work Hard, Play Hard, Publish

The inaugural PSI Winter School was meant to provide a glimpse of research life. Now it has produced a bonus: results.

It was meant to be a week in the snowy wilderness, where Perimeter Scholars International (PSI) students split their time between open research questions and outdoorsy Canadiana, far removed from the toil of their regular classes and tutorials.

Now, it has turned out to have been that and more.

Four of the students who attended Perimeter's 2016 PSI Winter School are co-authors of a research paper recently published in the journal *Physical Review B*, the largest and most comprehensive international journal specializing in condensed matter and materials physics.

A fifth student co-authored a paper relating to one of the Winter School research projects, and a third paper stemming from the week-long retreat is currently being finalized.

While PSI students publish papers each year, often related to their end-of-year research projects, no one attended the week-long retreat in Huntsville, Ontario, obliged to produce results.

"We wanted it to be as flexible and free as possible," said Perimeter Academic Program Director James Forrest. "The idea was to sit in a group, discuss things, think on your feet, and develop that research skill set."

Before the retreat, Perimeter faculty set out seven research challenges on which they suspected good progress could be made in a week. Then, a mix of Perimeter researchers joined the students to tackle the problems head-on.

"We had master's students, PhD students, postdocs, PSI fellows, and faculty all working together," Forrest said.

"It is one of the few, if not the only, time you had such a range of people working on a project together. If we didn't do the Winter School, these papers wouldn't have happened."

It's yet another unique aspect of the 10-month master's program. Only accepting roughly 30 students each year from more than 600 applicants, the program is quickly becoming one of the most sought-after physics programs in North America.

Lauren Hayward Sierens is a former PSI student who is now doing her PhD at Perimeter and the University of Waterloo. Together with Perimeter Associate Faculty member Roger Melko, she led one of the seven research projects at the 2016 Winter School.

It was their project, studying the entanglement entropy in free bosons on a lattice, which produced the recently published paper. In one week, the students learned to code in Python, then studied entanglement entropies for differently shaped regions.

"When you measure entanglement, the form you get depends on the shape of the region entangled," she said.

"In one dimension, there's an exact form. In two dimensions, we have models with a lot of the right features, but we still don't have the perfect model. We were able to show that the question isn't yet answered. There's more work to do in this field."

In the end, Forrest said the best lesson of all was a simple one: "Research is fun."

– Tenille Bonoguore

Applications for the 2017/18 PSI program are open until February 1, 2017.

The PSI program was supported in 2015/16 by:

Burgundy Asset Management; Joanne Cuthbertson and Charlie Fischer; The Hellenic Heritage Foundation; The Ira Gluskin and Maxine Granovsky Gluskin Charitable Foundation; The Kitchener and Waterloo Community Foundation – The John A. Pollock Family Fund; Brad and Kathy Marsland; Margaret and Larry Marsland; The Savvas Chamberlain Family Foundation; Scotiabank; and The Scott Griffin Foundation.

Movie Makeover

Acclaimed director Alexander Payne explains why Perimeter made the perfect setting for scenes from his forthcoming film, Downsizing.

For one morning last May, Perimeter Institute was transformed into Edvardsen Institute, a fictional Norwegian biomedical facility where scientists have discovered how to miniaturize people.

It was an alternate reality envisioned by Alexander Payne, the writer/director behind such critically acclaimed films as *Sideways*, *Nebraska*, and *About Schmidt*.

Payne – along with dozens of crew members, actors, and extras – filmed a pair of scenes for *Downsizing*, a science-fiction satire starring Matt Damon, Kristen Wiig, and Neil Patrick Harris, due for release in late 2017.

Although these A-listers were not part of the Perimeter shoot, the Institute itself is expected to play a key role in the film, since the opening shots – during which a Norwegian scientist realizes he has unlocked the secret to shrinking humans to miniature size – were filmed in the Atrium and Neil Turok's office.

After Payne wrapped filming, *Inside the Perimeter* sat down with the director to chat about the movie and Perimeter's role in it.

Inside the Perimeter: So what is *Downsizing* all about?

Alexander Payne: *Downsizing* is a film that imagines what might happen – or versions of what might actually happen – if, as a panacea to overpopulation and climate change, an independently funded Norwegian scientific organization discovers how to shrink people down to about five inches tall.

Inside: You first visited Perimeter with a location scout months before filming – what made you want to shoot here?

AP: Well, it was beautiful – physically beautiful. I can believe it exists in Norway. And, of course, its importance in the physics community is huge, and I was really honoured to think that we could even shoot here. It was right for the film – and it was a cool place to be!

Inside: Science fiction seems like a departure from your previous work.

AP: It is a science fiction premise, but we take it on in very human ways. Like all science fiction, it's really just a prism – an alternate way to look at contemporary problems. I think it was Ray Bradbury who was asked once, "Why do you only write science fiction? Why don't you write real stories?" And he said, "Don't you know science fiction is the only genre that really allows you to look deeply at things?" The film has a science fiction premise, but it's also a comedy.

Inside: Can you tell us what the Perimeter scenes are about?

AP: Today's scene is the very beginning of the film, and you're seeing the discovery of downsizing. Here, with the beautiful central atrium and then the director's office, we just considered this would have the correct feeling for a large scientific organization's building. I always like to get things as real and as right as I can in my movies.

Inside: What do you hope audiences will get out of *Downsizing*?

AP: I never want to control anyone's reading of a film – that's part of the fun. Of course, my ego always wants them to think "Boy, that was a good movie." But I know that, as an audience member, I am not fully entertained most of the time unless I'm also made to think somehow. One thing I've been really gratified by is that when I've told people the story of this film, they go: "You told me this idea and I can't stop thinking about it." Hopefully, it will give viewers a new prism to look at things through. But who am I to say what a film should be? I prefer when films are entertaining and funny and charming on some level – so I hope to God it's that.

– Interview by Colin Hunter

New Chair Builds Ties Between Perimeter and Greece

The Stavros Niarchos Foundation and Perimeter Institute for Theoretical Physics launched an $8 million partnership to fuel the research of theoretical particle physicist and Perimeter Faculty member Asimina Arvanitaki.

The Stavros Niarchos Foundation Aristarchus Chair in Theoretical Physics will not only support research into the universe at its most fundamental level, but will also foster outreach, research, and training ties between Perimeter Institute and Greece.

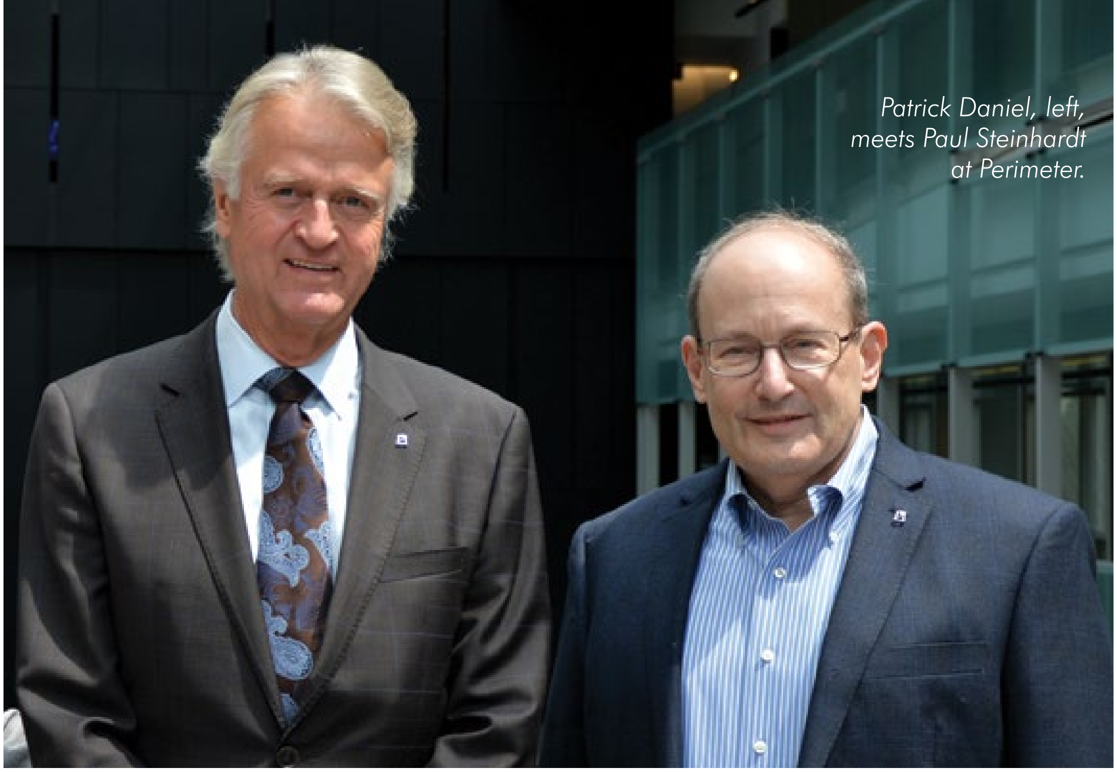
Arvanitaki's work explores novel experimental approaches to particle physics that may be done with small-scale experiments, rather than enormous colliders. Her research focuses on tests at the so-called "precision frontier," which uses experiments that are, in some cases, small enough to fit on a table top.

"May this important chair take you even further in your discoveries," said Kirsty Duncan, Canada's Minister of Science, at the chair launch ceremony last April. The event was attended by many dignitaries and friends of the Institute, including Ontario Lieutenant Governor Elizabeth Dowdeswell and Canadian Minister of Small Business and Tourism Bardish Chagger (MP-Waterloo).

For Andreas Dracopoulos, Co-President and Director of the Stavros Niarchos Foundation, Arvanitaki's appointment serves as a beacon for Greek science students. "Science owes so much to the art of imagination. To all of you at the Perimeter Institute, keep imagining, keep looking, for the good of humankind," Dracopoulos said.

Just months after the Chair was announced, Arvanitaki also received a $140,000 Early Researcher Award from the Province of Ontario, which will help to build her research team and bring researchers to Ontario for collaboration at Perimeter.

From left: Perimeter COO Michael Duschenes, Asimina Arvanitaki, Perimeter Founder and Board Chair Mike Lazaridis, and Stavros Niarchos Foundation Co-President Andreas Dracopoulos at the announcement of the Stavros Niarchos Foundation Aristarchus Chair in Theoretical Physics.



Patrick Daniel, left, meets Paul Steinhardt at Perimeter.

BUILDING A LEGACY THROUGH SCIENCE

By funding a new Visiting Research Chair at Perimeter, the Daniel Family Foundation aims to support research and collaboration that will make an impact for generations.

Despite a long career as one of the most successful executives in Canadian business, Patrick Daniel has always been, in many ways, a scientist at heart.

He obtained a master's degree in chemical engineering from the University of British Columbia before embarking on a career that would see him become President and CEO of Enbridge Inc., a publicly traded energy delivery company. His Enbridge leadership, and roles as director of the Canadian Imperial Bank of Commerce and Cenovus Energy Inc., led to his being named Canada's Outstanding CEO of the Year by Caldwell Partners.

When he retired in 2012, Daniel turned his priorities to his philanthropic interests – and to his longstanding passion for science. Not long after establishing the Daniel Family Foundation, he was introduced to Perimeter and was captivated by the Institute's pursuit of the deepest questions in fundamental physics.

The foundation turned that interest into support, pledging $300,000 to create The Daniel Family Richard P. Feynman Chair in Theoretical Physics (Visiting) at Perimeter Institute, to enable leading cosmologist Paul Steinhardt of Princeton University to spend up to three months every year conducting intense research and collaborating at Perimeter.

Inside the Perimeter caught up with Daniel this past July when he visited Perimeter to meet with Steinhardt and the Institute's leadership, and to get a "mental workout" with some fundamental physics.

Inside the Perimeter: What sparked your involvement with Perimeter?

Patrick Daniel: I was first introduced to Perimeter by Joanne Cuthbertson, who is on the Perimeter Board, a very well-known Calgarian and a good friend of mine. She explained to me a little about Perimeter, and I was actually quite surprised to hear that this world-class facility existed in Canada. I've always had kind of a technical and scientific mind, so it got my attention immediately. I have a very long-lasting interest in basic scientific research, and an understanding that it provides the foundation for so many things we take for granted in society today.

Inside: This is your first visit to Perimeter. First impressions?

PD: Well, it's overwhelming! It's like being out of shape and going to the gym for the first time in five years, but this is a mental workout rather than a physical workout… It's very stimulating and mentally challenging!

Inside: But you've had some good personal trainers for the workout?

PD: Neil Turok took me through a number of the collaborative spaces and exposed me to some of the work that's going on right now. Over lunch, I had a chance to meet Mike Lazaridis, the brains and the passion behind the original establishment of the Institute. I also had lunch with Paul Steinhardt, who will occupy the Chair that my family is establishing, which will allow him to do some research here at the Institute. I don't pretend to understand a fraction of what I've heard today, but it's great to know that this kind of critical thinking is going on here. It's been an opportunity to meet with a number of people, see the facility, and catch a bit of the enthusiasm from the youth and students and all the people involved here.

Inside: What motivated you to start your family foundation?

PD: When you're in your career, you focus on accumulating and looking after your family. When you retire, you start to think about some kind of legacy... Through my many years in industry, I've always felt that basic fundamental research is lacking. Finding out that such an amazing facility is available in Canada and that you can support world-class research led me to get involved along with my family. My sons have technical minds – one is a surgeon and one is an engineer – and they both identify very well with fundamental research as a priority… I also wanted to pass that along to my grandchildren, so they would think about community support through their lives. I hope this becomes a family tradition. And I would love to see my grandchildren here someday, so they could get enthused – and maybe even be physics researchers themselves someday.

Inside: You mentioned Paul Steinhardt and the Chair your family foundation has helped create. What inspired you to support his research?

PD: To have someone like Paul, who is based at Princeton and will be coming here regularly, I think it brings an outside influence that is critically important. He pointed out to me: "We don't want this to be a closed-door institute at Perimeter. We want the doors to be open so people from around the world can come in, bring expertise with them, and take away expertise." I am sure he is going to do great work, and its impact might not be measurable or recognizable in a decade – or even a hundred years – but that's how fundamental research is. Coming from business, where we're too often very short-term and near-term-minded in what we do, to have the opportunity to think and invest longer term is very important.

– Interview by Colin Hunter

Tall Tales and True Discovery

Introducing Paul Steinhardt, the Daniel Family Richard P. Feynman Chair in Theoretical Physics (Visiting)

When Paul Steinhardt was a child, his father told him amazing tales of daring heroes and courageous heroines. But the stories that really captivated him were even more fantastical. They were tales of science.

"I don't quite know why he did that; he wasn't a scientist himself, he was a lawyer," Steinhardt said during a graduation address to the PSI class of 2015.

"He used to tell me a story of Madame Curie or Louis Pasteur or Galileo, which would build to a climax in which there was a moment of discovery. And wow, that to me was the most exciting story, much more exciting than the other fairy tales. It made me want to be one of those discoverers."

Today, Steinhardt is a cosmologist with a singular impact on physics. He not only helped create both of the leading – and competing – models of the cosmos, he introduced the idea of quasicrystals and, after years of searching, ultimately found them in nature.

Currently the Albert Einstein Professor in Science at Princeton University and Director of the Princeton Center for Theoretical Science, Steinhardt now also holds the Daniel Family Richard P. Feynman Chair in Theoretical Physics (Visiting) at Perimeter Institute.

The appointment means Perimeter will be Steinhardt's research-home-away-from-home for three years. In many ways, it's a perfect match: Steinhardt conducts the kind of path-breaking research that Perimeter was created to foster.

One of the original architects of the inflationary model of cosmology, Steinhardt has since become one of its leading critics. In 2002, he and Perimeter Director Neil Turok proposed an alternative: the "cyclic model" of the universe, in which the big bang might instead be a big bounce. The cyclic model posits that bounces occur at regular intervals, and the current epoch of accelerated expansion will eventually slow, halt, and reverse, leading to the next big bounce. (See related story on page 6.)

In 1984, he and his student introduced the idea of quasicrystals. In 1998, Steinhardt launched a search of the world's mineral collections to find a quasicrystal in nature. A sample found in the mineralogical collection of the Museo di Storia Naturale in Florence, Italy, prompted an expedition to the remote Kamchatka Peninsula in eastern Russia.

There, in 2011, the team found a naturally occurring quasicrystal embedded in a 4.5-billion-year-old meteorite – making it older than the Earth itself. They later discovered a second natural quasicrystal in the samples, and Steinhardt had a third crystalline phase named after him.

His quasicrystal studies have also incorporated Medieval Islamic tiling patterns, and led to the development of novel materials for controlling the flow of light in photonic devices. He now has more than 10 patented technologies, some of which may be useful in future quantum technologies.

It's a track record that exemplifies Steinhardt's approach: be bold, be curious, and respect the data.

"New discoveries can be found everywhere. You just have to know the right question to ask," he said.

– Tenille Bonoguore

THANKS TO OUR SUPPORTERS

ENDOWMENT FUND

FOUNDER ($150M+)
Mike Lazaridis

$25M+
Doug Fregin

$10M+
Jim Balsillie

GOVERNMENT PARTNERS

Government of Canada
Government of Ontario
Region of Waterloo
City of Waterloo

ENDOWED INITIATIVES

BMO Financial Group Isaac Newton Chair in Theoretical Physics ($4 million)
Stavros Niarchos Foundation Aristarchus Chair in Theoretical Physics ($4 million)
The Peter and Shelagh Godsoe Family Foundation Award for Exceptional Emerging Talent ($1 million)

PERIMETER RESEARCH MAJOR GIFTS

Carlo Fidani, in support of the Centre for the Universe ($5 million)
Mike and Ophelia Lazaridis Niels Bohr Chair in Theoretical Physics ($4 million)
Gluskin Sheff Freeman Dyson Chair in Theoretical Physics ($2 million)
John Templeton Foundation – Templeton Frontiers Program at Perimeter Institute ($2 million)
Krembil Galileo Galilei Chair in Theoretical Physics ($2 million)
Krembil William Rowan Hamilton Chair in Theoretical Physics ($2 million)
Clay Riddell Paul Dirac Chair in Theoretical Physics ($1 million)
Cenovus Energy James Clerk Maxwell Chair (Visiting) in Theoretical Physics ($300,000)
Daniel Family Richard P. Feynman Chair (Visiting) in Theoretical Physics ($300,000)

CORPORATE AND SPONSORSHIP PARTNERS ($100,000+)

BMO Financial Group, Presenting Sponsor, Perimeter Public Lecture Series
Maplesoft, Perimeter Educational Outreach Champion
RBC Financial Group, Presenting Partner, International Summer School for Young Physicists

AWARDS ($50,000+)

The Savvas Chamberlain Family Foundation Anaximandros Fellowship
The Joanne Cuthbertson and Charlie Fischer Graduate Student Award
The Scott Griffin Foundation Honorary PSI Scholarship Award
The Hellenic Heritage Foundation Anaximandros Fellowship
The Brad and Kathy Marsland Honorary PSI Scholarship Award
The Margaret and Larry Marsland Honorary PSI Scholarship Award

ACCELERATORS CIRCLE ($50,000+)

The Cowan Foundation
Corinne Squire and Neil Turok

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

DIRECTORS CIRCLE

$25,000+

Robin and Robert Ogilvie

Donald and Eleanor Seaman Family Foundation

$10,000+

Denise and Terry Avchen - Environmental Research Advocates

The Boardwalk

The Kitchener and Waterloo Community Foundation

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

Ildiko and Peter Paulson

Robert and Pearl Radnitz

The TRH Foundation

Alex White

FRIENDS

$5,000+

Michael Duschenes

Dorian Hausman

Hopfmueller Family

Stephen Lister and Dr. Molly Rundle

Renée Schingh and Robert Myers

$2,500+

Jerome Bolce

John Matlock

Reid Family

$1,000+

Debbie and Ian Adare

Doug Brock

Ben and Mona Davies

J. DesBrisay and M. Cannell

Greg Dick

Lori-Anne Gardi

Edward Goldenberg

Michael Horgan

Frederick Knittel

Ann Leese and Irwin Rotenberg

Ron and Shirley Levene

Stefan and Shani Pregelj

Van der Veen Family

$250 to $999

Stephanie, Robert, and Aaron Hilson

Colin Hunter

Sheri and David Keffer

Ed Kernaghan

Robert Lake

W. Michael Roche

Jacqueline Watty

… plus 3 anonymous Friends donors

EMMY NOETHER CIRCLE

FOUNDING DONOR ($105,000)

The Bluma Appel Community Trust

EMMY NOETHER PROGRAMS AND AWARDS ($250,000+)

The Ira Gluskin and Maxine Granovsky Gluskin Charitable Foundation

$25,000+

Linamar Corporation

Scotiabank

$10,000+

Burgundy Asset Management Ltd.

Deloitte

Florence Minz

$5,000+

Patrice E. Merrin

Dr. Scott and Sherry Vanstone

$2,500+

Maria Antonakos and Harald Stover

Heather and John Clark

Jennifer Scully-Lerner

$1,000+

Andrea Grimm

Vicki Saunders

Steven and Suzan Wilson - Rebel Homes Inc.

$250 to $999

Alexandra Brown

GIFTS OF CELEBRATION, HONOUR, AND MEMORY

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

Simon Haysom, in memory of Elsie Haysom

IN-KIND GIFTS

Steinway Piano Gallery Toronto

This list reflects gifts received between August 1, 2015 and November 11, 2016, and multi-year commitments of $50,000 and more.

Shaping Community

In Perimeter, donors see another turning point in the evolution of a community.

An airy, cerebral research institute where the latest ideas in theoretical physics take shape around equation-filled blackboards may seem light years away from a manufacturing plant floor where durable cutting dies and molds are made.

But to Ronald and Shirley Levene, who are annual Perimeter Institute donors, the connection was obvious from the time they saw the Institute rising out of the ground more than a dozen years ago.

To the community-minded couple, Perimeter's creation was another foundational step in Waterloo's evolution, part of the unique tapestry where workers and thinkers, arts and culture, ideas and manufacturing, come together.

It added a new dynamic to the city where, in 1923, Ronald's great-grandfather, Sam Levene, founded the Ontario Die Company. The company, which makes dies and molds for the automotive and food industries, is today known as ODC Tooling & Molds, and employs about 100 people in Waterloo.

"Having Perimeter Institute here, along with all the technology companies, really enhances and builds on what the city has grown to become," Ronald says. "This is a very vibrant community and this is an important part of that vibrancy."

The Levenes are big supporters of the many threads that weave a community – from the apprenticeship programs that supply labour to the community's manufacturing base, to hospitals and educational institutions, as well as arts and culture.

They often attend concerts at Perimeter. "The talent and calibre of the musicians is really great," Ronald says.

He also appreciates that Perimeter brings young researchers and their families into this mosaic. "We need youth for the city to continue growing. Having facilities like this attracts young families and that enhances the growth of the city. As the city grows, it becomes more attractive and their children will stay," he adds.

The Levenes support young people in their own business, training and sometimes employing students through apprenticeship and co-op programs at Conestoga College and the University of Waterloo.

The Levenes' eldest son, Casey, is the fifth generation to work in the family business. Their youngest son, Elli, who is not yet directly involved in the family business, is an environmental sciences graduate, as well as photographer and videographer. A physics aficionado, he has enjoyed many Perimeter Public Lectures.

Their middle son, Leejay, died in 2007. His memory lives on in the annual memorial Leejay Levene Calendar (www.leejaylevene.com), a project headed by his mother. Proceeds support a different charity every year; the 2017 calendar, now on sale, is in support of the Juvenile Diabetes Research Foundation. It is a huge undertaking, Shirley says, but is something that, in her son's name, "helps to make the community whole."

Making the community whole – helping it grow and become a good place to live – is what drives the Levene family, and their support of Perimeter.

"It is an honour to have this facility here," Shirley says. Ron adds: "We are proud of it."

– Rose Simone

To learn more about becoming a Perimeter donor, please contact Jacqueline Watty at jwatty@perimeterinstitute.ca.

We're coming....

INNOVATION150

A nationwide program from five leading science outreach organizations that celebrates Canada's innovative past and sparks ideas and ingenuity to propel our future. Led by Perimeter Institute, this Canada 150 Signature Initiative inspires, excites, and engages Canadians from coast to coast to coast.

60+ COMMUNITIES VISITED WITH TRAVELLING SCIENCE EXPO

100,000+ YOUTH ENGAGED FACE-TO-FACE

13 PROVINCES AND TERRITORIES

5–7 INNOVATION FESTIVALS

UNLIMITED IDEAS AND INNOVATIONS FOR CANADA'S FUTURE

Visit **Innovation150.ca** to learn more.

A CANADA 150 SIGNATURE INITIATIVE

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

actua Youth · STEM · Innovation

UNIVERSITY OF WATERLOO | IQC Institute for Quantum Computing

Canadian Association of Science Centres · CASC · ACCS · Association canadienne des centres de sciences

CANADA SCIENCE AND TECHNOLOGY MUSEUMS CORPORATION
SOCIÉTÉ DES MUSÉES DE SCIENCES ET TECHNOLOGIES DU CANADA

CANADA 150

Canada

Dan's Kickin' Kimchi

black hole bistro

Everyone knows there are a whole bunch of microbes living in our bodies, but we don't often take care of them. I think that fermented foods tend to make them more happy, and that seems to make me happy. Things like kombucha, sauerkraut, kimchi, pickles, tempeh, and kefir seem to give me an energy boost. They are also super delicious!

Here is a recipe for kimchi that we use in the Black Hole Bistro. Kimchi is the ultimate condiment – crunchy, spicy, salty, sour, and sweet. You can put it on almost anything, but a few of my favourites are fried rice, fish dishes, burgers, and tacos.

– Dan Lynch, Black Hole Bistro Manager

Quick and Simple Kimchi

(Modified from www.thekitchn.com)

INGREDIENTS (Makes 1 quart)

1 head Napa cabbage (about 2 lb)
1/4 cup sea salt or kosher salt
1 tablespoon grated garlic (about 5-6 cloves)
1 teaspoon grated ginger
1 teaspoon sugar
2 tablespoons fish sauce
3 tablespoons Korean red pepper paste Gochujang
8 ounces daikon, peeled and cut into matchsticks
4 scallions, trimmed and cut into one-inch pieces

EQUIPMENT

Cutting board and knife
Large bowl
Gloves
Plate and something to weigh the kimchi down, like a jar or can of beans
Colander
Small bowl
Clean one-quart jar with canning lid or plastic lid
Bowl or plate to place under jar during fermentation

1. Prep the cabbage. Slice the cabbage lengthwise into quarters and remove the cores. Cut each quarter crosswise into two-inch-wide strips. Place the cabbage and salt in a large bowl. Using your hands (gloves optional), massage the salt into the cabbage until it starts to soften a bit, then add water to cover the cabbage. Put a plate on top and weigh it down with something heavy, like a jar or can of beans. Let stand for two hours. You are using the salt to extract the water from the cabbage.

2. Rinse and drain the cabbage. Rinse the cabbage under cold water three times and drain in a colander for 15 minutes. Rinse and dry the bowl you used for salting, and set it aside to use in step 5.

3. Make the paste. Combine the garlic, ginger, sugar, and fish sauce in a small bowl and mix to form a smooth paste.

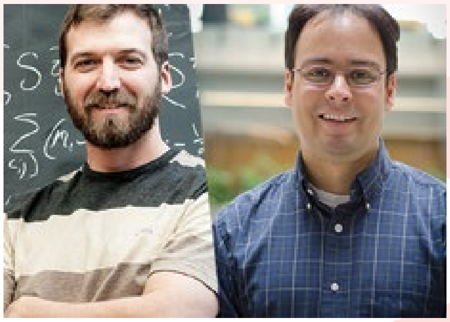
4. Combine the vegetables and paste. Gently squeeze any remaining water from the cabbage and return it to the bowl along with the radish, scallions, and seasoning paste. Mix thoroughly to ensure that the paste covers all the vegetables and cabbage.

5. Pack it in. Pack the kimchi into the jar, pressing down on it until the brine rises to cover the vegetables. Leave at least one inch of headspace. Seal the jar with the lid.

6. Ferment! Let the jar stand at room temperature for one to five days. You may see bubbles inside the jar and some brine may seep out of the lid; place a bowl or plate under the jar to help catch any overflow.

7. Watch, then chill. Check the kimchi once a day, pressing down on the vegetables with a clean finger or spoon to keep them submerged under the brine. (This also releases gases produced during fermentation.) Taste a little at this point, too! When the kimchi tastes ripe enough for your liking, transfer the jar to the refrigerator. You may eat it right away, but it's best after another week or two.

Canadian Association of Physicists prizes go to Perimeter Faculty



Two Perimeter researchers whose work explores the complex realms of quantum entanglement and high energy particle physics have been awarded medals from the Canadian Association of Physicists. Freddy Cachazo, the Gluskin Sheff Freeman Dyson Chair in Theoretical Physics, has won the prestigious CAP-CRM Prize in Theoretical and Mathematical Physics. Condensed matter theorist Roger Melko was awarded the CAP Herzberg Medal, which honours outstanding achievement by a Canadian physicist early in their career. Melko is an associate faculty member at Perimeter and holds the Canada Research Chair (Tier 2) in Computational Many-Body Physics at the University of Waterloo. "These awards recognize exceptional work by two leading scientists whose impact on their respective fields only promises to increase," said Perimeter Faculty Chair Robert Myers.

Three New DVRCs

The Perimeter research community has welcomed three new Distinguished Visiting Research Chairs. John Cardy is an Emeritus Fellow at the University of Oxford and a visiting professor at the University of California, Berkeley, who currently works on quantum many-body systems. Scott Aaronson is a theoretical computer scientist at the University of Texas at Austin whose research focuses on quantum computing and computational complexity theory. Xiao-Gang Wen resumes his DVRC position after four years as a Perimeter Research Chair. Their appointments bring the number of Perimeter DVRCs to 52.

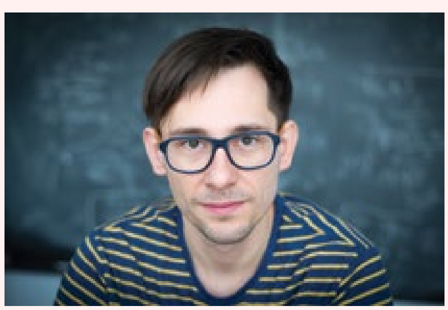
"Slice of PI" Wins CSWA Award

Perimeter's monthly "Slice of PI" won the 2015 Science in Society Communications Award at this year's Canadian Science Writers' Association conference. The Institute's Communications, Publications, and Audio Visual teams were commended for the work, which shares great science in fun and interesting ways. Sign up on the Perimeter website to receive them in your inbox each month!

Outreach Network Teachers win CAP Award for Excellence in Teaching

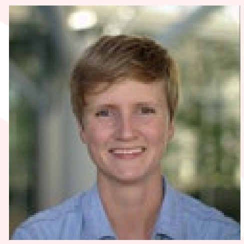
Two teachers in Perimeter's Educational Outreach Teacher Network won national awards from the Canadian Association of Physicists recognizing excellence in the classroom. Steve Greer, a teacher at Charles P. Allen High School in Bedford, Nova Scotia, and Jeff Goldie, a teacher at Strathcona High School in Edmonton, received 2016 CAP Awards for Excellence in Teaching High School/CEGEP Physics. "I'm simply a teacher trying to inspire students to wonder about the universe and help them find their passion. It's refreshing and motivating to know that there's a community of professional physicists supporting teachers. I appreciate and welcome this wonderful support," Greer said.

Perimeter Postdoc Wins Prestigious Grant



High energy physicist Michal P. Heller will set up a research group at the Max Planck Institute for Gravitational Physics in Potsdam, Germany this December, after winning a prestigious €1.65 million Sofja Kovalevskaja Award from the Alexander von Humboldt Foundation. Heller – who came to Perimeter specializing in using string theory to describe nuclear physics – shifted focus during his Perimeter postdoc toward the growing links between high energy physics and quantum information. His research group will probe emerging relationships between quantum information, quantum field theories, and geometry. "This discipline is not very well represented in Europe because it's brand new, so I want to be one of the seeds that's going to start an explosion there," Heller said.

PSI Grad Lauded for HIV Work



Imogen Wright, one of the first graduates from Perimeter Scholars International, has won second prize in the Innovation Prize for Africa for her work on Exatype, a software solution that enables healthcare workers to determine HIV positive patients' responsiveness to antiretroviral drug treatment. Wright is co-founder of Hyrax Biosciences, a social entrepreneurship venture that develops cost-effective ways to do genetic testing. "I draw massively on the method of abstract thinking that doing a lot of theoretical physics teaches you," she says. "If the average computer scientist can go to three or four levels of abstraction from whatever the underlying data is that they're looking at, by the end of PSI, I could go to seven or eight."

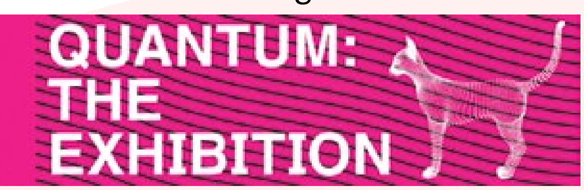
CAP Represents Canada in Asia

The Canadian Association of Physicists and Asia-Pacific Center for Theoretical Physics signed a memorandum of understanding in June to promote cooperation between the agencies in leading theoretical physics research. The three-year term aims to promote research, facilitate collaboration, and contribute to the advancement of physics in the Asia-Pacific region. Perimeter Institute is a funding partner of the CAP.

Honours Add Up for Turok

It's been a big year for Perimeter Director Neil Turok. In the fall, he received the highest honour of the Institute of Physics when he was named an IOP Honorary Fellow. This came just weeks after Turok won the John Wheatley Award from the American Physical Society for his work founding and leading the African Institute for Mathematical Sciences. He earlier won the John Torrence Tate Award for International Leadership in Physics, and in October travelled to London, England, to present this year's Gerald Whitrow Lecture at the Royal Astronomical Society.

QUANTUM Exhibit Is Coming



Next year's Innovation150 celebrations got a head-start in October when QUANTUM: The Exhibition opened at The Museum in Kitchener, Ontario. Put together by the Institute for Quantum Computing, the exhibition is designed to make quantum science and technology accessible to everyone. The fully bilingual exhibit features 4,000 square feet of interactive displays and creative storytelling, aimed at demystifying the emerging quantum technologies expected to shape the 21st century. It is one of the key elements in the year-long, nationwide program celebrating Canada's sesquicentennial, and will travel across Canada throughout 2017, aiming to inspire the next generation of Canadian innovators.

AIMS Opens Sixth Centre

African Institute for Mathematical Sciences

The African Institute for Mathematical Sciences opened its sixth centre, in Kigali, in August. AIMS-Rwanda's first cohort of 44 students includes 17 women, with students hailing from 10 countries. The centre's programs are specifically designed to attract female students into STEM areas of learning. Through its postgraduate training, public engagement, teacher training, and industry programs, the centre is expected to contribute to Rwanda's national goals for gender equity in education. Meanwhile, the Canadian government committed \$19.6 million over five years to the AIMS-Next Einstein Initiative to train African mathematical scientists to develop climate change adaptation and mitigation solutions. And the University of Regina finalized a partnership agreement with AIMS to provide both financial support and an academic exchange between the organizations.

Maplesoft Partners as Educational Outreach Champion

Maplesoft

Mathematical software company Maplesoft is partnering with Perimeter's Educational Outreach Team to support the Institute's Teacher Network, EinsteinPlus workshop for teachers, and the International Summer School for Young Physicists. As an Educational Outreach Champion, the Canadian company will also provide complimentary product licences to students and teachers within Perimeter's orbit, and support the development of online educational resources. "Maplesoft technology, combined with PI's innovative programs, will build a stronger foundation for students, provide a bridge between high school curriculum and university-level education, and enhance university-readiness in STEM courses," said Jim Cooper, President and CEO of Maplesoft.

Beam Me Up

In August, William Shatner interviewed Neil Turok for a TV documentary called *The Truth Is in the Stars*, about the enduring influence of *Star Trek* on science, popular culture, and innovation. Shatner and Turok chatted on the deck of the USS Intrepid in New York City, at its Space Shuttle Enterprise exhibit. Perimeter Faculty member Avery Broderick, a longtime *Star Trek* fan who credits the show for sparking his love of all things space, was interviewed for the documentary as well. Scheduled to air in 2017, the film also features interviews with other scientific leaders including Chris Hadfield, Elon Musk, and Stephen Hawking.

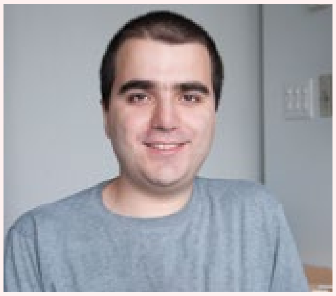
The Americas Come to Perimeter

Fifty delegates from 27 countries visited Perimeter Institute in September to learn how fundamental, collaborative research helps spur an ecosystem of innovation. The visit was part of the sixth Americas Competitiveness Exchange (ACE), which aims to share best practices and stimulate new collaborations that can help turn ideas into tangible innovations. In a keynote presentation to the group, Perimeter Founder and Board Chair Mike Lazaridis discussed the Quantum Valley ecosystem, which spans theory, experiment, and commercialization of emerging technologies. "In order to build the Quantum Valley, we needed a very strong foundation in theoretical physics," Lazaridis said. "The cooperation of the government, academics, and the region allowed us to get a lead, and that gives us a competitive advantage going forward as the world explores quantum technologies." The ACE tour also included the Institute for Quantum Computing and the Communitech Hub in Waterloo Region, and stops in Toronto, Hamilton, and the Niagara Region.

Associate Faculty Member Wins IQSA Prize

Perimeter Associate Faculty member and current Canada Research Chair (Tier 2) in the Foundation of Physics at Western University in Ontario, Markus Mueller is one of two winners of this year's Birkhoff-von Neumann Prize from the International Quantum Structures Association. The prize committee said Mueller "has established himself, in a remarkably short time, as one of the leading figures working at the intersection of quantum information theory and the foundations of quantum theory."

Pedro Vieira Appointed to New International Collaboration



Pedro Vieira, who holds the Clay Riddell Paul Dirac Chair in Theoretical Physics, is part of a new global initiative funded by the Simons Foundation called the Simons Collaboration on the Non-Perturbative Bootstrap. The four-year collaboration, directed by Leonardo Rastelli of the C.N. Yang Institute for Theoretical Physics, intends to map and understand the whole space of quantum field theories, including strongly coupled models. It promises to "cross traditional boundaries between string theory, condensed matter physics, and phenomenology, while making strong connections to modern mathematics and computer science."

THE HOTTEST TICKET IN TOWN

Featuring authors, musicians, cosmologists, philosophers, and more, this year's Perimeter Institute Public Lecture Series will take audiences – in person at Perimeter and watching online – to the edge of knowledge, at the frontier of discovery.

In eight lectures, from October to June, a dynamic lineup of presenters will:

- explore how quantum information will impact technology, finance, and cybersecurity;
- provide an inside look at the next generation of space telescopes;
- bring an update from the forefront of stem cell research;
- share the magic of mathematics;
- and much more.

Tickets to the lectures are free, but they are snapped up fast each month. To stay ahead of the crowd, sign up for reminders about Perimeter events at www.perimeterinstitute.ca/site/mailing-list, or consider becoming a Perimeter donor: people who give more than $250 get access to Advanced Ticketing.

Can't make it to Waterloo? No worries. Every lecture is webcast live on Perimeter's website, as well as by media partners around the world. Viewers can live-tweet with Perimeter scientists during the talk (hashtag #piLIVE), and submit questions online for the post-talk Q&A.

If you miss a lecture, all are online at www.Youtube.ca/PIOutreach. Last year's lectures have received more than 324,000 views, and counting. To keep up-to-date on who is speaking when, and for information about how to get your (free!) tickets, visit www.perimeterinstitute.ca/publiclectures.

PRESENTING SPONSOR

BMO

Watch lectures from this season now at www.YouTube.com/PIOutreach: October 5: Michele Mosca on the new quantum era; November 2: Michael Cates explains inexplicable liquids; December 7: Molly Shoichet on the promise of regenerative medicine.

Stay tuned for details on upcoming speakers, and save the dates now: February 1, March 1, April 5, May 3, June 7.

STAR TREK TECHNOLOGIES: SCIENCE FICTION OR SCIENCE FACT?

2016 is a landmark year for science fiction: the original Star Trek *is turning 50! Now that we are living in the future, among physicists who have been inspired by the Trek vision, we get to ask them: is* Star Trek *possible?*

Are transporters possible?

Avery Broderick: Why wouldn't transporters be possible? We can already use quantum mechanics to teleport things as big as molecules. There's a lot of scaling up to do between a molecule and a person, but as physicists like to say, that's an engineering problem.

The biggest challenge is probably not the actual transporter, but the information processing required to keep track of that many quantum particles. Also, you have to destroy the original to create the duplicate, so I'm not sure I'd sign up for the test run.

Avery Broderick is an Associate Faculty member at Perimeter Institute and the University of Waterloo. He says he became a physicist "because Star Fleet doesn't exist." He's an astrophysicist with a particular interest in black holes.

Is warp drive possible?

Adrienne Erickcek: The "warp drive" is aptly named: the most probable way to travel faster than the speed of light is to warp spacetime. Einstein's theory of special relativity states that nothing can go faster than the speed of light, but his theory of general relativity permits a loophole: it may be possible to contract space in front of a ship and expand space behind it in such a way that the ship could reach its destination at faster-than-light speeds.

Unfortunately, warping space in this way would require a tremendous amount of energy, and the resulting distortion of spacetime would likely destroy everything at the ship's destination. That's not the friendliest way to make first contact!

Adrienne Erickcek is an Assistant Professor at the University of North Carolina at Chapel Hill and was a postdoctoral researcher at Perimeter from 2009 to 2013. She's a theoretical cosmologist whose research focuses on dark matter, dark energy, and the universe's first second.

Are tractor beams possible?

Stephanie Keating: Not only are tractor beams possible, they actually already exist – at least, in a limited sense. Two years ago, physicists created a tractor beam that uses a hollow laser, which is dark in the centre and bright around the edges. The laser heats up particles, which become trapped in the centre of the beam. This kind of tractor beam can move very tiny particles distances up to a few metres.

Last year, scientists created another sort of tractor beam: a sonic one that uses sound waves timed in a very precise way. This creates a pocket of low pressure, allowing you to trap objects and move them around through the air.

Now, we're not quite trapping spaceships yet. These were just "proof of concept" experiments, done on fairly small scales. But larger versions could one day be created for shifting bigger objects through 3D space. We could imagine practical purposes for these beams – like moving goods in warehouses, for example.

Stephanie Keating was an astronomer before she joined Perimeter Institute's publications team as a science writer. If she had a tractor beam, she'd use it to swoosh her cat's toys (but not her cat) around the house.

Hey kids! Have a question? Send it to magazine@perimeterinstitute.ca.

Classical World Artists *Series* 2016/17

Angèle Dubeau & La Pietà

Thursday, November 24, 2016 | 7:30 PM

Chamber Music Society of Lincoln Center

Thursday, January 19, 2017 | 7:30 PM

Christian Tetzlaf, violin, Lars Vogt, piano

Monday, February 13, 2017 | 7:30 PM

David Fray, piano

Tuesday, May 9, 2017 | 7:30 PM

Details at
perimeterinstitute.ca/tickets
Ticket Office 519.883.4480

Scan here for more info

Supported by:

The Kitchener and Waterloo Community Foundation
- Musagetes Fund

Perimeter cultural and bistro events are ancillary activities made possible through paid ticketing, private donors, and sponsorships.

JUST ONE BREAKTHROUGH IN
PHYSICS CAN CHANGE EVERYTHING.

THE PERIMETER EQUATION IS SIMPLE:

FOSTER BREAKTHROUGH RESEARCH.
TRAIN THE NEXT GENERATION
OF PHYSICS PIONEERS.
SHARE THE POWER OF THEORETICAL
PHYSICS WITH THE WORLD.

$$\boxed{\int \text{Be Part of} \overset{\text{(the)}}{=} \Sigma\text{quAction}^2}$$

Please consider supporting Perimeter
at www.perimeterinstitute.ca/donate
or by contacting Jacqueline Watty at
jwatty@perimeterinstitute.ca.

PERIMETER PI INSTITUTE FOR THEORETICAL PHYSICS

Ontario Canada

Charitable registration number: 88981 4323 RR0001

www.perimeterinstitute.ca