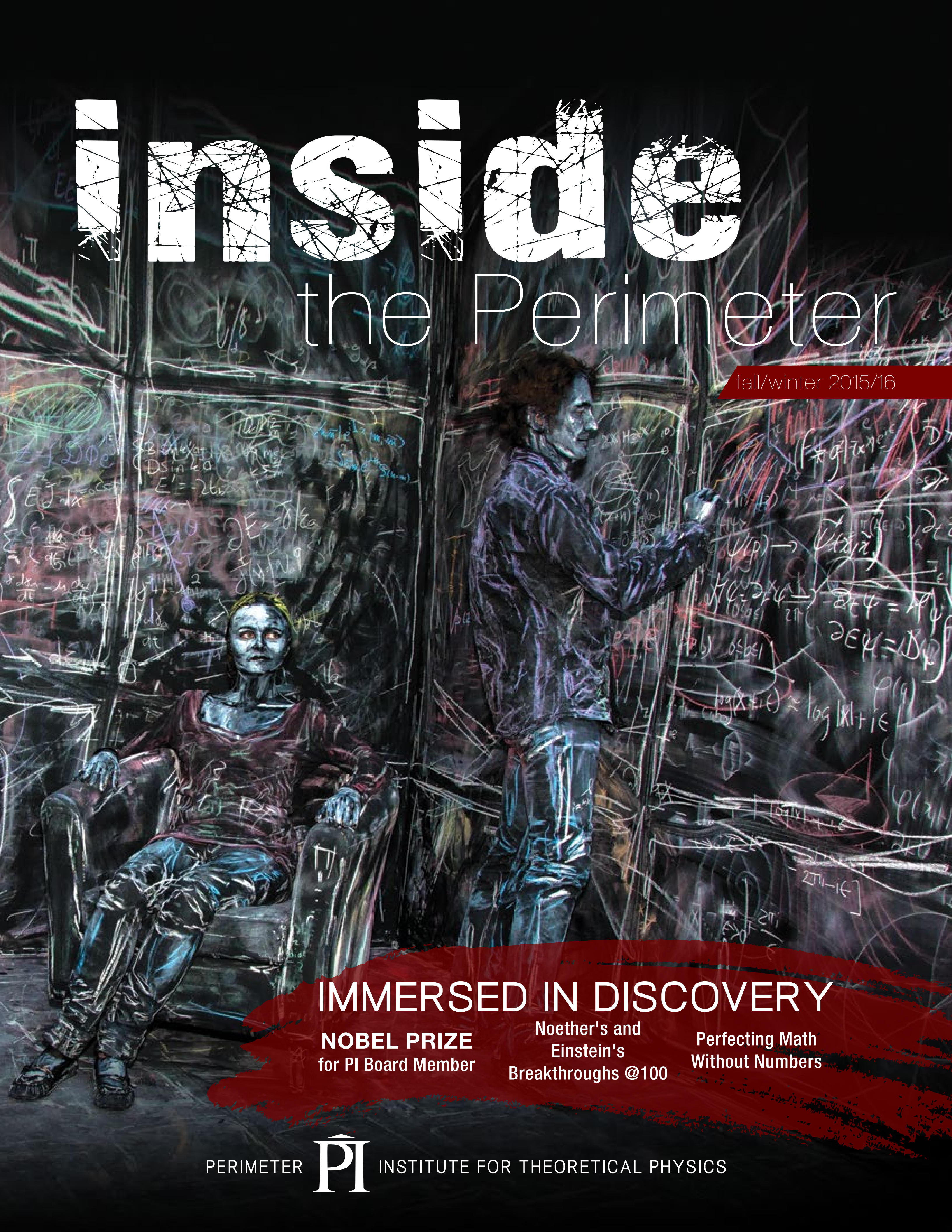
inside the Perimeter

fall/winter 2015/16



IMMERSED IN DISCOVERY

NOBEL PRIZE for PI Board Member

Noether's and Einstein's Breakthroughs @100

Perfecting Math Without Numbers

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

inside the Perimeter

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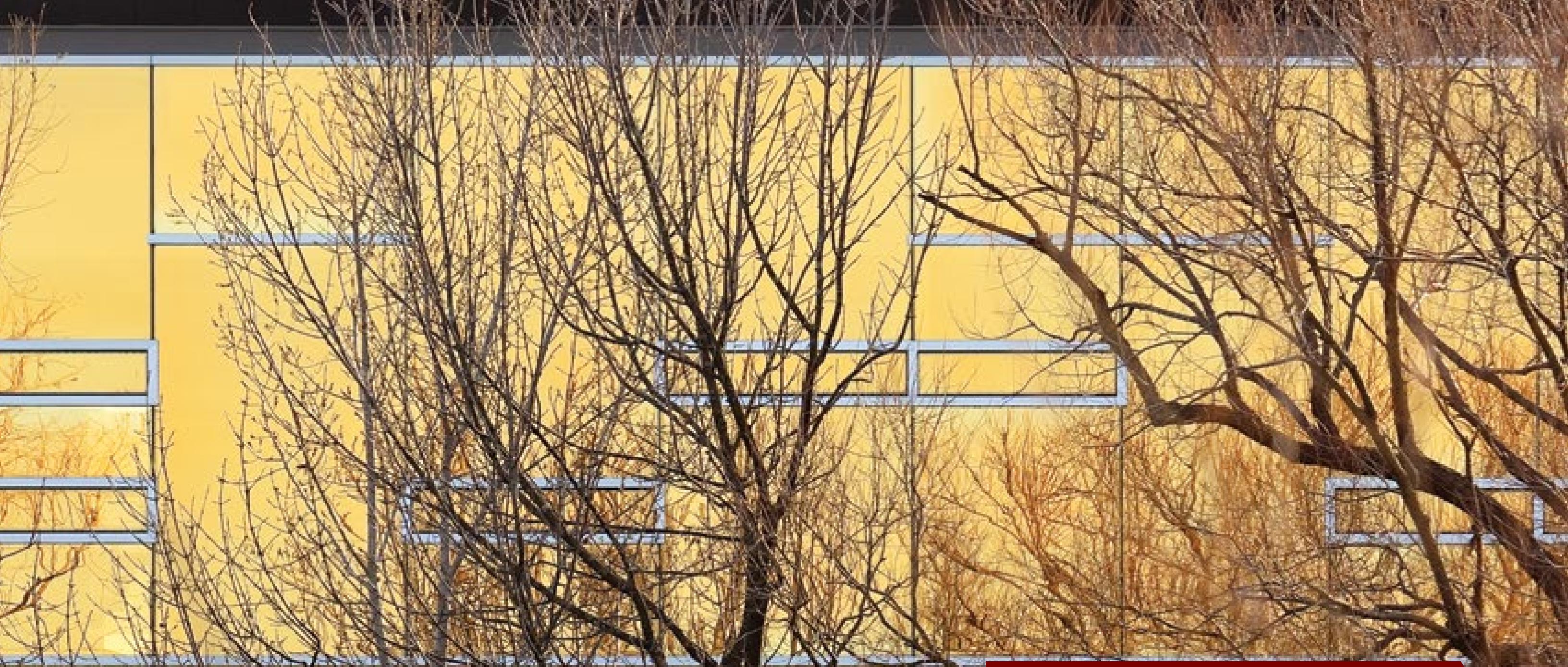
This issue of
***Inside the Perimeter* is dedicated to**
Leo Kadanoff
colleague, mentor, teacher,
and friend.



IN THIS ISSUE

A New Golden Age

A hundred years ago in Berlin, Albert Einstein finally homed in on the definitive version of general relativity, his spectacular explanation of the law of gravity. The full drama and the manuscript he submitted on November 25, 1915 are beautifully presented in Hanoch Gutfreund and Jürgen Renn's new book, *The Road to Relativity*. There was even a race with the world's top mathematician, David Hilbert, but Einstein somehow got there first: as Hilbert's paper says, "The differential equations of gravitation that result here are, as it seems to me, in agreement with the magnificent theory of general relativity established by Einstein."

Einstein's theory transformed our understanding of space, time, and the universe. But his theory was only the beginning. Relativity has been an engine of discovery as physicists have explored the host of phenomena which it allows and describes – ranging from black holes to dark energy and the expanding universe. Just as important, quantum mechanics – the other great pillar of 20$^{\text{th}}$ century physics – is at odds with general relativity, and the tension between the two continues to drive fundamental physics today.

We physicists have a funny way of showing our love for a great theory: we do our best to overthrow it. We are delighted when it works, as we expect relativity will when the Event Horizon Telescope reveals the structure of the black hole in our Milky Way, or LIGO detects the gravitational waves emitted when two black holes merge. Both developments are expected in the near future. But we are even more delighted when a theory reveals its cracks and flaws, because these are indications of new physics still to be discovered. For all its elegance and power, general relativity is not the final theory of the universe. We know it fails at the big bang and inside black holes. In reconciling it with quantum theory, we hope to make the next great leap forward.

Thus we are not celebrating the 100$^{\text{th}}$ anniversary of this perfect diamond of a theory; rather, we are celebrating 100 years of pushing it to the limit. For 100 years, general relativity has prevailed in test after test, on Earth, in the solar system, and beyond – to the entire visible universe. But we are now pushing it even further, towards describing the big bang itself, the most violent astrophysical phenomena, the largest and the smallest distances ever probed. At the same time, new mathematical connections between quantum gravity and quantum fields are emerging, taking us beyond traditional approaches and providing clues to new theories.

In seeking new physics, the universe around us is always our best guide. The puzzles it presses upon us are the best clues to new theories. In the 1960s, particle physicists found that the number of neutrinos coming from the sun did not match the number predicted by the prevailing theory. Neutrinos are very hard to detect, so, for a while, many dismissed the "solar neutrino puzzle" as a possible experimental error. But as time went on, and the puzzle was confirmed by other experiments, it became harder to ignore. So physicists set out to explain it.

Here in Canada, it was tackled at the Sudbury Neutrino Observatory (SNO), an ingenious experiment led by Art McDonald. When I joined the faculty at Princeton in 1988, I just missed him: Art had just moved to Canada. But I used to frequently hear his name (in reverence!) and wondered who he was. Twenty years later, when I moved to Canada, I finally met Art at Queen's University. A couple of years later, in 2011, we were delighted to welcome Art to Perimeter's Board of Directors. Art had shown amazing entrepreneurship in returning to Canada to design and build the world's top experimental laboratory for neutrinos, in a nickel mine in Sudbury, Ontario. Somehow, Art persuaded the Canadian nuclear agency to loan him a huge supply of heavy water as a target for the neutrinos, and to guarantee them and the insurers that it would be safe in his hands! SNO ultimately resolved the solar neutrino puzzle by showing that neutrinos change from one "flavour" to another as they travel to Earth. This mixing of flavours demonstrates that neutrinos have a tiny mass, and the best explanation involves physics at enormous energies, close to those where quantum gravity is important. So the SNO finding is another great clue to the physics beyond Einstein's theory.

We were thrilled when we heard Art had been co-awarded the 2015 Nobel Prize and were delighted to be able to celebrate with him in person a few weeks later (see page 6). In every conversation or email exchange we've had, the first thing he says is that the Nobel is not for him, but for the team he led – specially the hundreds of students who were trained on the experiment, which ran for years and has now grown into a scientific powerhouse, SNOLAB.

Art is, of course, modest and Canadian – but he is also right. Great science is almost always a team effort. At the end of the opening paragraph of his great paper on general relativity, Einstein says, "I want to acknowledge gratefully my friend, the mathematician Grossmann, [who] helped me in my search for the field equations of gravitation." Even developing the most abstract theory can be, and benefits from being, a very social activity (see page 10).

Indeed, a beautiful illustration of this came almost immediately after Einstein presented his theory of general relativity. Trying to understand mathematically how gravitation was compatible with the conservation of energy, David Hilbert invited a promising young mathematician, Emmy Noether, to help work through the knots. In the course of doing so, she achieved a breakthrough of her own. Noether's theorem, which states that for every symmetry in nature there is a conservation law, is now part of the bedrock of physics.

(If you're never heard of Noether, by the way, you're not alone. Despite the fact that it's hard to imagine modern physics without her, she is not a well-known historical figure, nor did she get the respect she deserved in her lifetime. Perimeter's efforts to change the way women are treated in physics are named after her for a good reason, which you can read more about on page 18.)

Here at Perimeter, we have an extraordinary challenge, as well as an exceptional chance: to develop the ideas that will reshape our understanding of the universe, just as Einstein did. Bold as this mission may be, there has never been a better time. We are living in a golden age of data, from the Large Hadron Collider to the Planck Satellite, and an abundance of experiments in between. Information is being gathered at an unprecedented pace. What it is revealing is a universe with astonishing, although deeply puzzling, simplicity. A universe requiring new principles of physics.

– Neil Turok is Director of Perimeter Institute.

Major Awards Recognize a Scientific Work of Art

Perimeter Board Member and valued colleague scores two career coups in one month, sharing the 2015 Nobel and Breakthrough Prizes.

After spending much of his career two kilometres underground, Art McDonald was thrust into a bright spotlight this fall when he shared the 2015 Nobel Prize in Physics for his landmark work on neutrino oscillations at the subterranean SNOLAB near Sudbury.

The honour was quickly followed by the Breakthrough Prize in Fundamental Physics, recognizing McDonald's team and four other neutrino research groups worldwide.

For the humble McDonald, professor emeritus at Queen's University and a member of Perimeter's Board of Directors, the awards were an opportunity to highlight the team efforts that make great science possible.

"This is a tremendous honour for me and my Canadian and international collaborators on the SNO experiment," McDonald said of the recognition. "We are very pleased to have been able to add to our scientific knowledge in a very fundamental way."

The discovery that neutrinos can flip between their three types – changing from electron neutrinos to muon neutrinos to tau neutrinos and back again – was a truly great piece of science. Like many great scientific breakthroughs, it both resolved a long-standing anomaly and opened doors to new understandings.

Experts on solar fusion had calculated how many neutrinos emitted by the sun should reach Earth, but experimentalists only found about a third of the predicted number. This was the solar neutrino anomaly. Either physicists did not understand the sun, or they did not understand neutrinos.

To nuclear and particle physicists like McDonald, the fact that exactly two-thirds of the neutrinos were missing was suggestive. Neutrinos were known to come in three types, but neutrino detectors could detect only one of them: the electron neutrino (the type emitted by the sun). But what if the sun's electron neutrinos could shift to muon or tau neutrinos en route? These muon and tau neutrinos would pass by undetected – and two-thirds of the solar neutrinos would appear to be missing.

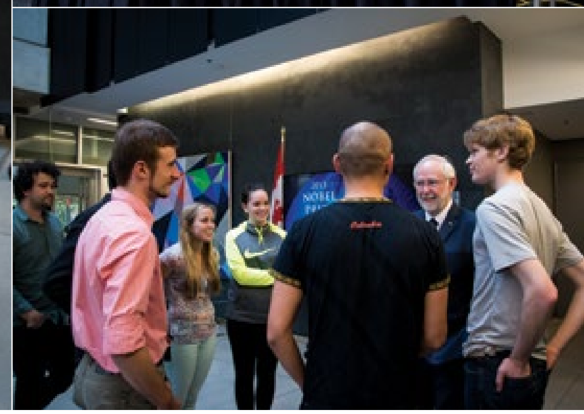
It was an interesting hypothesis, facing two big challenges. First, the idea that neutrinos can change type requires them to have mass. (Basically, they are allowed to shift because of quantum uncertainty, and the mass is the source of that uncertainty.) But the Standard Model of particle physics required massless neutrinos. At that point, the Standard Model had explained all experimental results and resisted all experimental challenges for more than 20 years. The idea that it might be wrong was radical.

Second, the prospect of measuring all three neutrino types was daunting. Measuring neutrinos at all is difficult, but detecting those that can only interact via fleeting and rare muon and tau physics seemed nearly impossible.

The experiment to find the missing neutrinos would be ambitious and difficult – but it seemed possible. And it happened in Canada, at what would come to be called the Sudbury Neutrino Observatory, or SNO. Art McDonald was a leader in early discussions about SNO and was elected its director in 1991.

Why Canada? Atomic Energy Canada had more than a tonne of heavy water stockpiled, and using heavy water would allow experimentalists to measure all three types of neutrinos. The Creighton Mine in Sudbury, among the deepest in the world, offered a suitable site: putting the experiment two kilometres underground would block most of the roar of background radiation, allowing the tiny whispers of the neutrino signals to be heard.

It took almost 10 years to build the experiment and make it work, but it did work. SNO announced the discovery of neutrino oscillation in 2001.



This one discovery – that neutrinos can change their type, and therefore have mass – has changed our understanding of the innermost workings of matter. As the Nobel committee wrote, “new discoveries about [neutrinos’] deepest secrets are expected to change our current understanding of the history, structure, and future fate of the universe.”

Perimeter hosted a congratulatory reception for McDonald shortly after the Nobel announcement, during which he likened Perimeter's collaborative, ambitious atmosphere to that of SNOLAB.

▲ *Clockwise from left: Neta Bahcall and Art McDonald; Mike Lazaridis, Neil Turok, and Art McDonald cut the celebratory cake; PI residents speak with the new Nobel laureate.*

“From an engineering point of view, what we were trying to do [at SNOLAB] was pretty difficult,” said McDonald. “But from an intellectual point of view, what you’re doing here is massive, and you’re doing it very well.”

– Erin Bow and Colin Hunter

Further Exploration: Learn more about neutrinos with *Symmetry* magazine’s cool interactive www.symmetrymagazine.org/standard-model

The system worked beautifully – for a while. Then, *zap*!

As a graduate student at Princeton in the early 1980s, Robert Myers needed to get his hands dirty.

He had aspirations to do theoretical research in quantum gravity, but the university insisted he get hands-on lab experience before beginning his PhD studies. So, at the urging of a friend, Myers nervously knocked on the door of Art McDonald.

Myers and McDonald, it turned out, had already spent years in close proximity to one another: Myers grew up in the northern Ontario town of Deep River, near Chalk River Laboratories, a nuclear research facility where hundreds of scientists – including McDonald for 12 years prior to his Princeton professorship – worked.

Myers needed lab experience. McDonald had brought a polarized electron source to Princeton from Chalk River, and he needed help getting it running in the basement of Princeton’s Jadwin Hall. “He gave me a tour of the lab, described the project, then told me to get to work,” Myers recalls.

So Myers got to work, wiring up the power supplies and counters, always keenly aware of the encroaching deadline to qualify for PhD studies. One day, McDonald popped down to join Myers in the lab and began taking measurements of electron polarization.

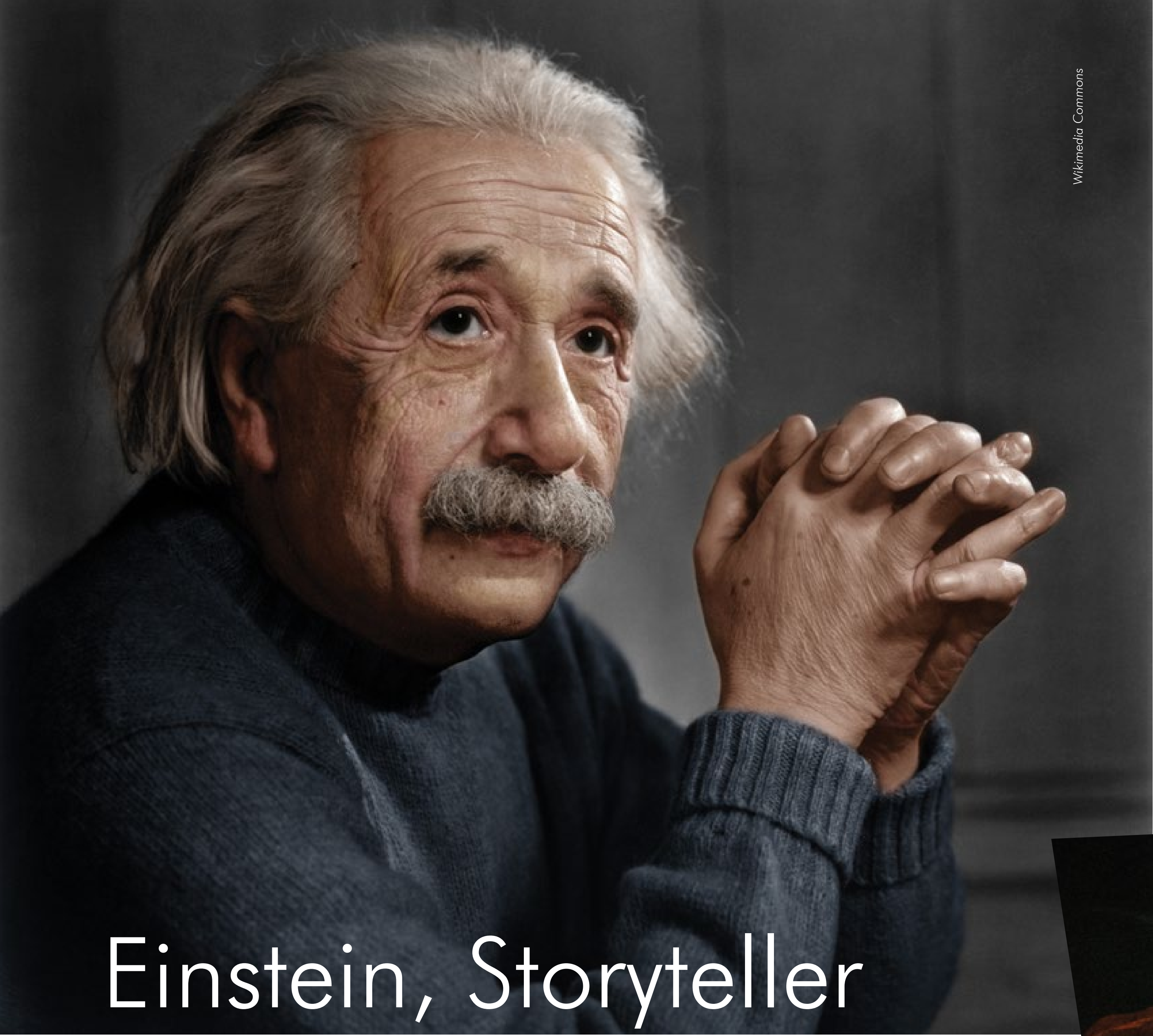
The system worked beautifully – for a while. Then, zap! An electrical arc shut down the apparatus and blew the lighting fuses, leaving Myers and McDonald standing in the dark.

“Well,” an amused McDonald told his protégé in the darkness, “I guess your work here is done.”

McDonald went on to win a Nobel Prize for his work in experimental physics. Myers got into the PhD program but stuck with theoretical physics, eventually becoming a founding faculty member at PI.

But Myers has always been grateful to the mentor who allowed him to tinker in the lab. “My first thought when Art won the Nobel: it couldn’t have happened to a nicer guy,” says Myers.

– Colin Hunter



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Einstein, Storyteller

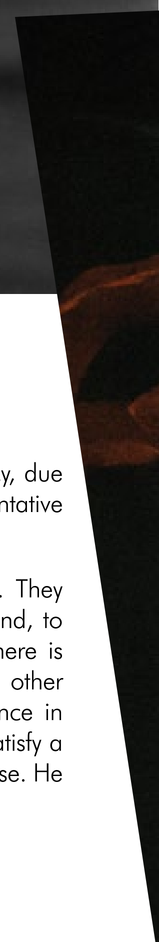
For quantum gravity specialist and author Lee Smolin, Albert Einstein's greatest strength didn't lie in numbers.

Albert Einstein is singular.

When I study the papers of other great physicists, such as Galileo, Kepler, Maxwell, Bohr, Heisenberg, Schrödinger, and Dirac, I can understand who they are. They are extremely good scientists, but not different, in kind, from the best of my contemporaries. Einstein is different. (Newton is also different, but they are the only two.) After many years of study, I still find Einstein's unerring, surefooted ability to penetrate right to the heart of things to uncover the secrets of nature incomprehensible.

How did he do it? What makes Einstein different from the rest of us? What made him different from his contemporaries, and allowed him to make discoveries that others couldn't? With hesitancy, due to my appreciation of the subtlety of his thought, here is a tentative answer: Einstein was a storyteller.

Einstein asked different questions than his contemporaries. They were content to live with knowledge that was incomplete and, to a greater or lesser degree, contradictory or incoherent. There is nothing wrong with this. Most scientists, then as now, have other fish to fry – other goals than seeking the greatest coherence in our knowledge of the universe. But Einstein did science to satisfy a deep need to understand himself placed in a coherent universe. He disliked the patches and wrinkles in the fabric of physics.



He had, for instance, a storyteller's suspicion of coincidence. Newton had two notions of mass-inertial mass (or resistance to force), and gravitational mass (or weight). But the two masses always turn out to be equal. For everyone else, this equality of gravitational and inertial mass was just an extra condition to be imposed on the equations. For Einstein, this was a tremendous opportunity to discover a hidden coherence. Maybe, from the right point of view, gravity and inertia are the same.

He found that perspective in his thought experiment about a man in an elevator, unable to tell if he is sitting still on the surface of the Earth or pushing upward in empty space. This is the equivalence principle, which holds that you cannot tell the difference between an effect of gravity and an effect of inertia. It is, at heart, a story, and it is the key to general relativity.

There is a myth that Einstein was a lonely genius who followed beautiful mathematics to discover his great theory. Genius inspired by aesthetics; mathematics as a tool of prophecy. But, in fact, Einstein was neither very well educated in mathematics, nor very good at it. Nor did he work without collaborators. He depended on friends such as Marcel Grossmann to explain to him the mathematics on which general relativity is based, and he depended on other friends, such as Michele Besso, to find the correct interpretation of the mathematics.

What Einstein excelled at was physical intuition and insight. His path to general relativity was brightly illuminated by a simple physical idea: the equivalence principle.

Unfortunately, Einstein had no physical insights to guide his search for the uniting of quantum mechanics with gravity, which he called unified field theory. He had no new physical principles to propose, no new thought experiments to provoke his thinking. Unlike each of his prior successes – special relativity, photons, Brownian motion, and general relativity – Einstein was working without guidance from his formidable physical intuition. He was running, as Jackson Browne sings, on empty.

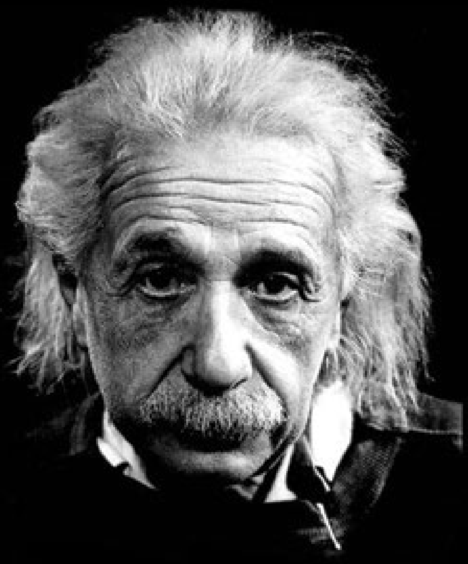
In the absence of a new story to tell, Einstein fell back on mathematics as his guide. He constructed a myth about how mathematical beauty had been prophetic for his invention of general relativity, and he attempted to use it to justify his forays into unified field theory. He became sadly lost there, and those who followed him into the swamp were lost, too.

Einstein succeeded when he was able to formulate a principle or hypothesis about nature, which he, or sometimes others, later expressed in mathematical terms; he failed when he attempted to use mathematics as a substitute for insight into nature. You can indeed use mathematics to unify gravity and electromagnetism (in fact I know of at least four ways to do so). But in the absence of a physical insight or principle explaining what the unification means, experimentally, the mathematical unification is empty.

So as we celebrate the birthday of general relativity, let us admire the Einstein who achieved that great step: a pragmatic but determined seeker after coherence; a physicist who had an unmatched power of insightfully getting to the hidden story at the heart of natural phenomena.

– Lee Smolin is a founding Faculty member at Perimeter Institute.

The Lone Genius*

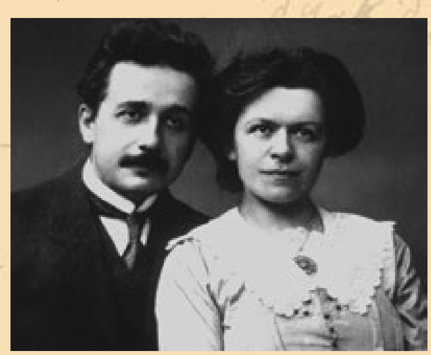


*WHO GOT BY WITH A LITTLE HELP FROM HIS FRIENDS

There's Einstein's theory of general relativity, and then there's the theory behind the theory. Two of them, actually. The most common is that Albert Einstein toiled alone until he presented his seminal paper on November 25, 1915. The other – which science historian Jürgen Renn says is more accurate – is that Einstein's masterwork was created with a lot of help from friends and colleagues.

"Einstein was not alone. He was surrounded by friends who supported his rebellious anti-authoritarian attitude with regard to the establishment of physics," says Renn, the director of the Max Planck Institute for the History of Science, who has spent years studying Einstein's original papers.

Here are some Einstein's key collaborators from 1905 (when Einstein published his special theory of relativity) to 1915 (when he published his general theory):

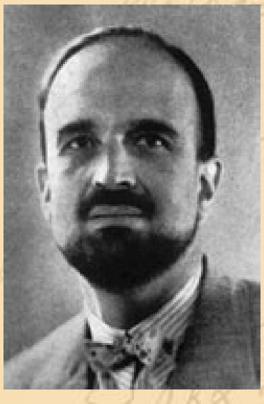


Mileva Marić: As classmates at university, Marić and Einstein developed an intense intellectual and romantic connection. They had a daughter (who either died or was given up for adoption), then married and had two sons. There is much debate over Marić's contribution to Einstein's early work, in particular special relativity. Most historians consider her a sounding board for Einstein, but a few academics posit she was closer to a co-author. The pair separated in 1914 – two years after Einstein became reacquainted with his cousin Elsa Löwenthal – and divorced in 1919. (Einstein and Löwenthal married later in 1919.)

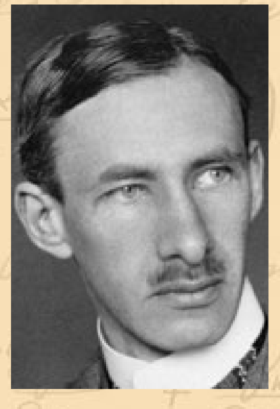
Marcel Grossmann: A former classmate upon whose lecture notes Einstein relied to pass university, Grossmann's father helped Einstein get a job as an assistant examiner in the Bern patent office after graduation. A specialist in descriptive geometry, Grossmann assisted with the math to create the field equations for general relativity, emphasizing the importance of Riemannian geometry and introducing Einstein to absolute differential calculus. Together, Einstein and Grossmann devised the "Entwurf" (draft) theory, a stepping stone between special and general relativity. In Einstein's notebooks, "you always see, in the crucial moments, Grossmann's name," says Renn.

Michele Besso: An engineer and patent clerk, "he was perhaps Einstein's most important interlocutor, not only during the time when he created general relativity, but through the rest of his life," Renn says. The pair constantly exchanged letters about everything, with Einstein using his friend as a sounding board for his latest ideas. Besso is credited with introducing Einstein to the works of Ernst Mach, whose thought experiments were central to Einstein's development of the equivalence principle.

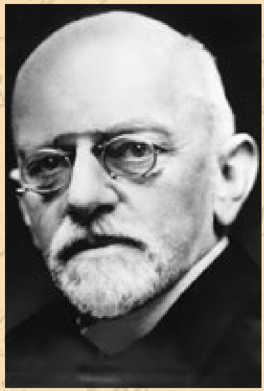
Erwin Finlay-Freundlich: The first astronomer to take Einstein's ideas seriously, Finlay-Freundlich worked at the Berlin Observatory, and was asked by Einstein in 1911 to make accurate observations of Mercury's orbit in order to confirm the general theory of relativity. Finlay-Freundlich's results were published in 1913 – against the recommendation of the Observatory Director. Einstein said Finlay-Freundlich was "the first among fellow-scientists who has taken pains to put the theory to the test." Finlay-Freundlich published a book in 1916 discussing ways to test general relativity with astronomical observations, and later became the chief observer at the Einstein Institute.



Adriaan Fokker: A Dutch physicist who worked as Einstein's assistant for the 1913-14 semester, Fokker co-authored a paper that contains Einstein's first treatment of a gravitation theory in which general covariance is strictly obeyed.



Paul Bernays: A mathematician and former classmate of Einstein and Grossmann, in 1914 Bernays advised the pair to use variational calculus in the formulation of the relativity theory.



David Hilbert: A mathematical genius at the University of Göttingen, Hilbert was introduced to the ideas of general relativity when Einstein visited in the summer of 1915. Taken with the theory, Hilbert emerged as a chief rival in completing it. The two exchanged letters as they raced to formulate the mathematical equations to support general relativity. Their rivalry peaked that November, during a series of lectures Einstein was presenting to the Prussian Academy: on November 15, Einstein's revised equations correctly predicted Mercury's perihelion drift; three days later, he received a letter from Hilbert revealing very similar work. On November 25, Einstein presented his completed final set of equations to the Academy. He had won the race, and the pair was soon making amends. Hilbert later noted, "Einstein did the work and not the mathematicians."

None of this diminishes Einstein's genius, Renn says. In fact, it helps underscore his brilliance, as he drew on and transmuted the knowledge accumulating in various branches of classical physics. "Einstein was a convergence thinker. He brought different traditions together."

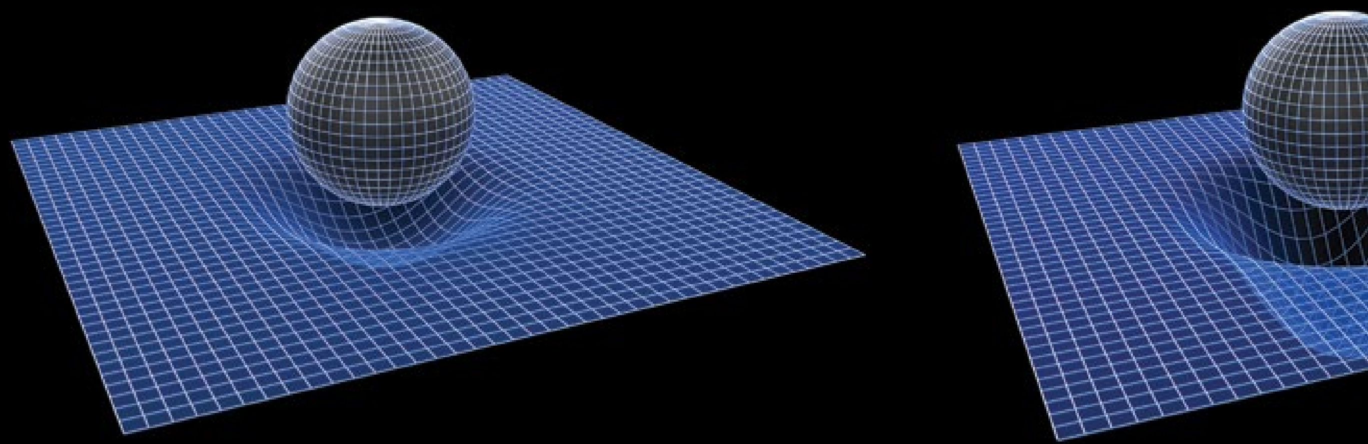
– *Tenille Bonoguore*

Further Exploration: Follow Einstein's progress in his own words at the Einstein Archives Online: www.alberteinstein.info

Watch Jürgen Renn's Convergence talk "The Genesis and Renaissance of General Relativity" on Perimeter's YouTube channel: www.youtube.com/PIOutreach

Gravity Beyond 100

Three Perimeter faculty look to the next 100 years of general relativity



Lifting the Veil of the Universe

Luis Lehner on gravitational wave astronomy

General relativity may be turning 100 this year, but the era of gravity is just beginning.

We are pushing gravity to explain some of the most mysterious and powerful events in the universe – things like black holes, quasars, and galactic jets.

In a sense, we are like Newton and the apple. Newton famously developed a theory of how an apple falls, but that by itself would not have been interesting. It was not until he pushed his theory of how an apple falls to explain how the planets orbit that gravitational theory was born.

Likewise, we must push general relativity, which was born as a theory of ordinary gravitational objects, like the apple, or the Earth, or the sun. It has been very successful at predicting how light bends or how planets orbit. Even fairly extreme events like two pulsars orbiting each other at large distances are within its comfort zone. But now we must test general relativity as a theory of strong gravity. We need to take those two pulsars and crash them into each other.

We have made theoretical progress in understanding strong gravitational events like colliding pulsars and black holes. Using general relativity, we predict that such events would produce large ripples in spacetime itself, which we can catch as gravitational waves.

We are standing on the edge of being able to see these waves for the first time. New detectors – LIGO and VIRGO – are beginning to turn on. We are at the dawn of gravitational astronomy. We are like Galileo when he first lifted a telescope to the sky.

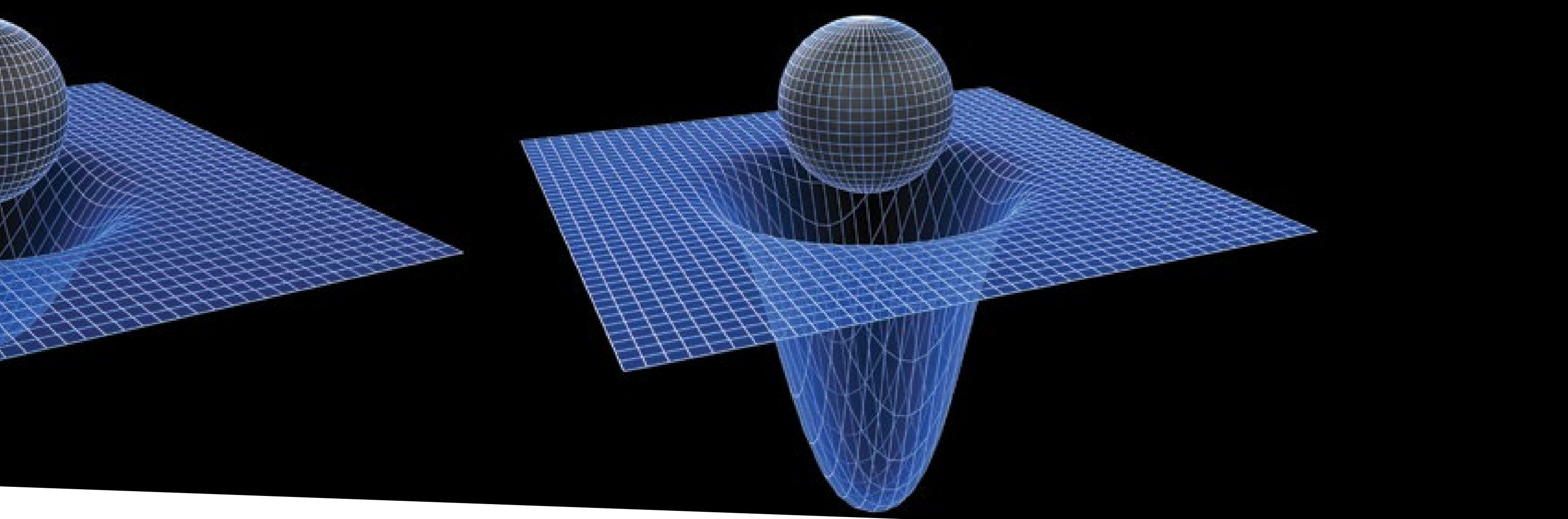
What will be the first thing we see? Two black holes colliding? A neutron star falling into a black hole? We are going to be able to probe gravity directly in the places where general relativity has predicted the most radical concepts. This may tell us how the theory fails, and where. That may guide a new gravity revolution.

But even if we see exactly what we expect, we will be seeing the sky with a whole new set of tools. We will make progress explaining the astrophysics of enigmatic events, like gamma ray bursts or galactic jets. We may get clues about dark matter or dark energy, which dominate our universe but about which we know almost nothing. We may someday even be able to ask questions about the extra dimensions and extra forces.

Truly, we do not know what we might see. But we know that the veil of the gravitational universe is about to be lifted.

– Luis Lehner is a Faculty member at Perimeter Institute who specializes in strong gravity.

General relativity is turning 100 this year, and physicists are looking back on a century of predictions come true. But even as we celebrate, we look forward. Here are three windows onto the future of gravitational physics.



Seeing Through the Dark

Avery Broderick on using black holes as gravitational laboratories

I think the future of gravitational physics might be just outside of a black hole.

Black holes are great natural experiment – it's almost as if they're designed to put general relativity to the test. They have the twin virtues of being extraordinarily simple solutions to Einstein's equations and of being the place where Einstein's predictions about gravity differ most sharply from Newtonian ideas about gravity. If we could see a black hole clearly, we could see whether general relativity really holds up in extreme conditions.

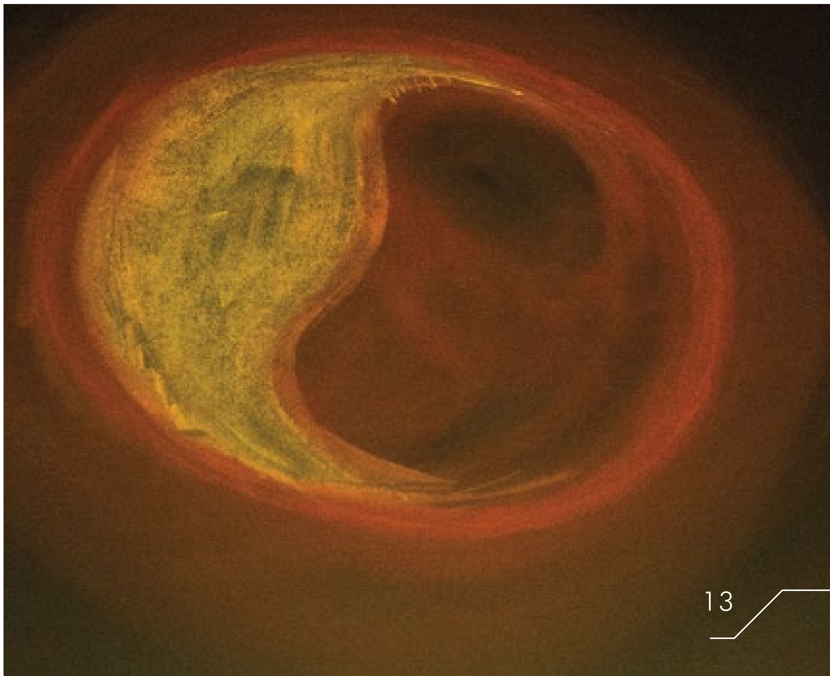
The good news is, that's becoming possible.

The Event Horizon Telescope is even now taking an image of a black hole at the centre of our galaxy, Sagittarius A*. The crucial point is that we can actually see the event horizon of the black hole – the outer skin that cloaks the singularity. The resolution this requires is extraordinary. The horizon of Sagittarius A* has an apparent size of about 55 microarcseconds; a microarcsecond is a third of a billionth of a degree. That's 450 times smaller than anything that can be resolved by the Keck telescope. That's 2,300 times smaller than can be resolved by the Hubble. That's the size of a poppy seed on the other side of a continent.

In short, we are looking at the universe with new eyes, more deeply and more sharply than ever before. And hand in hand with the new data, we have new theoretical understandings about what kind of signatures would distinguish a black hole that's totally obeying general relativity from a black hole that's doing something a little bit different. We know what to look for, and we're beginning to be able to look. We have a number of new techniques, some of them improving in capability by orders of magnitude, which I think will herald a golden age in black hole observation.

What might we see? We don't know, but personally I'm hopeful that it will be something new, something that will give us a better handle on what gravity must be doing. It may even be that the effects of quantum gravity might be observable at these scales. If they are, then this might be the point, like the turn of the last century, when all of a sudden the puzzle pieces click into place.

– Avery Broderick is an Associate Faculty member at Perimeter Institute who specializes in black holes.

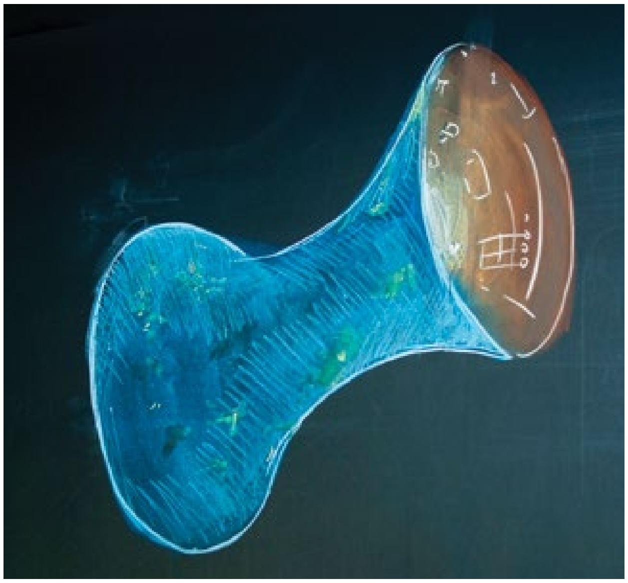


Gravity in a Hologram

Robert C. Myers on holography

One of the most remarkable ideas to emerge from string theory – which began as an attempt to unify Einstein's general relativity and quantum mechanics – is known as the AdS/CFT correspondence. This correspondence sets up a mathematical equivalence between quantum systems and objects in a gravitational field. Specifically, it states that gravity in a peculiar kind of spacetime called anti-de Sitter space (or AdS) is equivalent to a special kind of quantum field theory, called conformal field theory (or CFT) in one less dimension. Since this correspondence relates theories in different dimensions, it is often referred to as "holography." (Recall that a hologram encodes a three-dimensional image on a flat two-dimensional film.)

As absurd as it first sounds, this is an idea that has survived the scrutiny of thousands of theoretical physicists over the past 25 years. One can think of the AdS/CFT correspondence as a bilingual dictionary, which says that there is one set of physical phenomena that can be described by two different languages. One language is gravity, a theory usually used to describe physics on very long scales in terms of geometry and the dynamics of spacetime; the other is quantum field theory, a language that usually describes physics on very small scales in terms of probabilities, wave interference, and particle interactions.



As is often the case with translation, most of the words sound very different in the two languages. A "black hole" in the gravity theory becomes a "thermal plasma" in the quantum field theory. However, sometimes the words have a common root. For instance, the temperature of the plasma corresponds to nothing other than the Hawking temperature of the black hole. (One of Stephen Hawking's most famous discoveries, made in the 1970s, was that black holes slowly release thermal radiation due to quantum effects near the event horizon.) Much of the research in holography over the past two decades has been detective work to fill out the dictionary.

The holographic equivalence gives us an extraordinary window on both gravity and quantum field theories. The bonus is that in the regime in which the gravity theory is relatively easy to work with, the corresponding quantum field theory is strongly coupled. That is, the standard textbook approaches fail, leaving the theory nearly impossible to work with. Thus we can use holography to calculate for quantum field theories in a regime where we simply had no previous approaches to calculating at all.

The caveat is these holographic calculations apply for special classes of quantum field theories that are not precisely the same as those that describe nature. Despite this, we've had some good hints that AdS/CFT provides useful insights and even benchmarks for what we might expect to see in real-world experiments. One of the most celebrated results in this regard states that a holographic plasma behaves like a near-ideal fluid. In technical jargon, we say that its ratio of shear-viscosity-to-entropy-density is extremely low – much lower than in any known fluids. Or it was until 2005, when experimentalists at the Relativistic Heavy Ion Collider discovered that a new phase of nuclear matter known as the quark-gluon plasma was exhibiting almost precisely the same near-ideal fluid behaviour found in holography.

Holographic research is also now reaching out to condensed matter physics, where the theoretical description of many phenomena is hampered by our inability to work with strongly coupled quantum field theories. It is hoped that holographic models may provide us with physical insights into new materials that become superconducting at relatively high temperatures. An important result discovered here at Perimeter through holographic calculations is known as the F-theorem, which tells us something about how all (2+1)-dimensional quantum field theories fit together – the kind of theories that may describe high-temperature superconductors.

In yet another direction, it seems that the physics of black holes may be connected – via holograms – to quantum information. A quantity called "entanglement entropy" has been found to give a measure of the correlations between the microscopic degrees of freedom in a quantum theory. Interestingly, entanglement entropy is a concept that comes from quantum information, where entanglement between the quantum bits (or qubits) is a resource that can be used for ultra-fast computing or ultra-secure communications. Holography encodes the entanglement entropy in the geometry of the spacetime of the gravity theory. This is a remarkable perspective, the implications of which we are still trying to understand.

In the last several years, a broad research program has been launched to bridge quantum information and quantum gravity. It's becoming one of the most exciting and fast-moving frontiers in physics. (*Editor's note: See the accompanying article "Quantum Information: A new lens to view quantum gravity" on page 28.*)

All of these results seem to be the tip of an iceberg – holography appears not just to provide a useful set of translational tools, but a whole new perspective. It seems possible that this is the right perspective to reconcile gravity with quantum theory – perhaps the biggest challenge in theoretical physics.

– Robert C. Myers is a founding Faculty member at Perimeter Institute who specializes in quantum fields and strings.

Attention teachers: Perimeter Outreach has an in-class teaching resource exploring the power and relevance of general relativity. It's just one of PI's teaching kits suitable for grades 9 through 12. perimeterinstitute.ca/outreach/teachers/class-kits

Former PI Postdoc Wins Young Scientist Prize

Joseph Ben Geloun was a postdoctoral researcher at Perimeter from 2010 to 2013. Now at the Max Planck Institute for Gravitational Physics in Germany, Ben Geloun is continuing the ambitious research program he started at PI: developing a physically and mathematically consistent model of the infinitesimally tiny grains of quantum spacetime.

Inside the Perimeter *caught up with him after he received word that he had won the Young Scientist Prize from the International Union of Pure and Applied Physics.*

Inside the Perimeter: What is the question that drives your work?

Joseph Ben Geloun: "What is spacetime?" General relativity gives us a universe in which spacetime is smooth. But quantum mechanics indicates that the geometry of spacetime must fluctuate on the smallest scales. Resolving these conflicting pictures is one of the longstanding and biggest issues in physics. Some progress has been made in the last decades, but no theory giving a unified picture is presently available.

Inside: What is the most challenging part of working on quantum spacetime?

Ben Geloun: Understanding what happens at such small scales without experimental guidance. We are investigating physics on the scale of the Planck length, about 10^{-35} metres. It is difficult to apprehend how small that is. The smallest scale accessible at particle colliders is the electroweak scale – about 10^{-18} metres. This is where our cutting-edge technology stops. But comparing an object that is 10^{-18} metres to an object of the Planck length is like comparing the moon to an atom! What is remarkable is that theoretical physics even allows one to investigate the laws of physics at that tiny scale.

Inside: What is your approach to the problem?

Ben Geloun: I take the point of view that our spacetime could be actually built from discrete "building blocks" of Planck-length size. Specifically, I am investigating a framework called tensorial field theory (TFT). In the way a Dirac field describes an electron, or a gauge field describes a photon, a tensorial field would describe an elementary particle of spacetime itself. My specialty is renormalization analysis – that is, using mathematical tools that allow physicists to take descriptions of systems at one scale and move seamlessly to descriptions at larger scales – something like the zoom lens on a camera.

Inside: What did you win the prize for?

Ben Geloun: With my collaborators, I proved that several TFTs are "asymptotically free." In essence, it means that, at a microscopic level, several TFT models evolve at higher and higher energies towards quite a simple model. In the opposite regime, at low energies, asymptotic freedom generally means that, at some point in its evolution, the model undergoes a drastic change; perhaps a phase transition occurs. A well-known theory having this property is quantum chromodynamics (QCD). In QCD, asymptotic freedom helps us understand how quarks couple to form new composite particles such as protons and neutrons. In TFTs, asymptotic freedom becomes interesting because it may help us understand how to get from a phase where spacetime is [made up of] apparently discontinuous building blocks to a smooth spacetime.

Inside: Is this work applicable to other areas?

Ben Geloun: There are many approaches to the quantization of spacetime. I hope first that my work is meaningful to some of them. There are follow-up works on our results in the field. Beyond that, they might be useful for field theories using nonlocal interactions, like effective field theories. In a different area, TFTs are statistical models, and our results might be important to mathematicians.

Inside: What was your reaction to winning the prize?

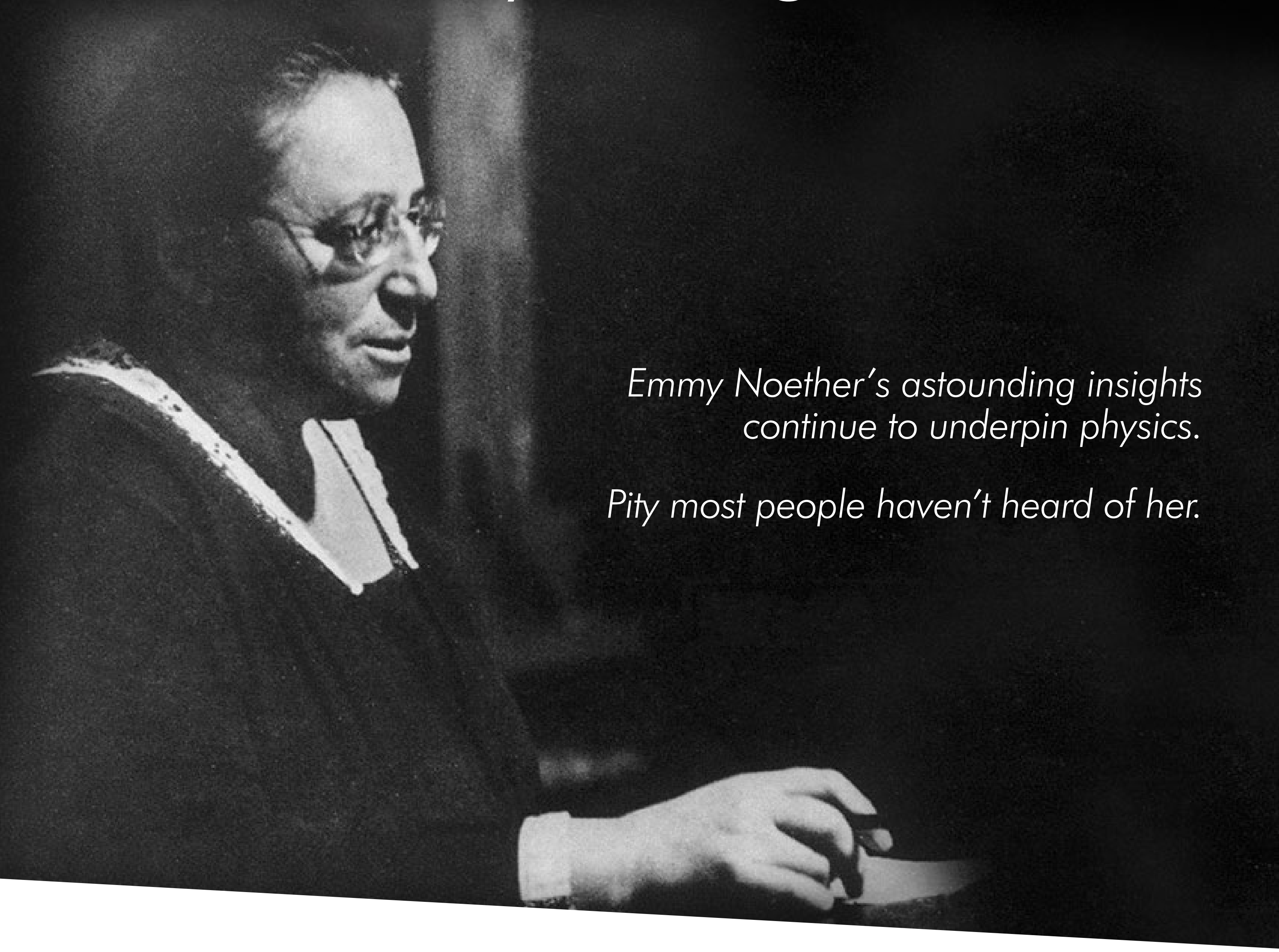
Ben Geloun: My first reaction was, of course, surprise. Then I felt privileged. A curious and unlikely path led me here. I come from Senegal and studying there, like in much of sub-Saharan Africa, is far from easy. Having a thought for the young African students there, I felt lucky. I wish to dedicate this Young Scientist Prize to the students in developing countries, in particular in Africa, studying in difficult conditions. I wanted to say to them: "This is also your time, your prize."

– Interview by Natasha Waxman

Further Exploration: J. Ben Geloun and V. Rivasseau, "A Renormalizable 4-Dimensional Tensor Field Theory," Commun. Math. Phys. 318, 69 (2013) [arXiv:1111.4997 [hep-th]].

J. Ben Geloun, "Renormalizable Models in Rank d ≥ 2 Tensorial Group Field Theory," Commun. Math. Phys. 332, 117 (2014) [arXiv:1306.1201 [hep-th]].

The Poetry of Logical Ideas



Emmy Noether's astounding insights continue to underpin physics.

Pity most people haven't heard of her.

To understand and visualize the new and elegant theory of general relativity, the physicists of the day needed a mathematical poet.

Her name was Emmy Noether.

Noether was a German mathematician who played with symmetry. Just as a poem has symmetrical qualities that make it lyrical to the ear, nature has internal symmetries: attributes that remain unchanged when a system goes through some other transformation.

In two landmark theorems, published in 1918, Noether described how conservation laws and continuous symmetry properties are intrinsically linked.

In a tribute to Noether published in the *New York Times* shortly after her death, Albert Einstein wrote "pure mathematics is, in its way, the poetry of logical ideas," and he described Noether as a master of the craft.

She was "the most significant creative mathematical genius thus far produced since the higher education of women began," he wrote.

Einstein's theory of general relativity, describing gravity emerging from the warping of spacetime, generated excitement when it was hot off the press in 1915.

Yet few are aware of his compatriot, who did groundbreaking mathematical work at around the same time, and whose influence resonates through every branch of modern physics today.

*

Amalie Emmy Noether was born in 1882 to a Jewish family in Erlangen, Germany, where her father, Max Noether, was a mathematics professor. She excelled at math-related puzzles even as a child, but she had to buck social convention to pursue mathematics at a time when a woman was expected to get married, have children, and perhaps, if she were to pursue a career, become a teacher in a girls' school.

So buck them, she did. The University of Erlangen did not allow women to enroll, so in 1900 she opted to become one of two women auditing classes alongside 984 male students. She then went to the University of Göttingen, where she audited lectures by famed astronomer Karl Schwarzschild and mathematicians Hermann Minkowski, Otto Blumenthal, Felix Klein, and David Hilbert.

In 1904, Erlangen began enrolling women. Noether returned to her hometown and, in 1907, received her PhD in the theory of invariants, a class of mathematical objects that remain unchanged when certain types of transformations are applied to them (such as the ratio of the circumference of a circle to its diameter staying the same no matter how big or small you make the circle).

Indeed, she became a "great calculator" of invariants, mathematician Peter Olver said during his Convergence lecture at Perimeter in June. Long before the advent of computational tools like Mathematica, Noether calculated all 331 invariants of ternary biquadratic forms for her thesis. (Noether herself would later describe that work as "manure," he added.)

"She just ignored social convention and did what she loved," says Ruth Gregory, a professor of cosmology and relativity at Durham University and Visiting Fellow at Perimeter Institute.

PhD in hand, but with no career path available to her, Noether worked at the Mathematical Institute of Erlangen, without pay or title, from 1908 to 1915.

1915 saw Noether at the University of Göttingen, then the world's leading centre for mathematics, where she collaborated with luminaries who had earlier been her lecturers. She still had no paid position.

In June of that year, Albert Einstein presented a lecture at Göttingen outlining the idea of general relativity. He had not yet worked out its mathematical laws, but the fledgling theory set the university alight.

Hilbert, in particular, was interested in working out the equations for Einstein's outline – perhaps even beating him to the formulation of relativity. But Hilbert quickly hit a snag: in his approach to general relativity, the conservation of energy law seemed to be violated. Knowing Noether's genius, Hilbert turned to her for help. What stemmed from that request was groundbreaking.

Noether realized that time symmetry is related to conservation of energy. Thanks to time symmetry, the laws of physics do not change from one day to the next. If it did, you could violate the energy conservation law, since you could lift a weight on a day when the gravity is low, and then lower it and extract extra energy the next day when gravity is stronger. But that can't happen, so time symmetry and energy conservation are linked.

This was an incredible insight. Here were two things that were seemingly unrelated – time and energy – but Noether was able to connect them using mathematics.

"It is hard to overestimate the importance of Noether's work and insights in modern physics," Gregory says. "The most important examples we end up using have symmetry in them. So I would regard Noether as enriching our understanding of relativity."

Today, Noether's theorems are used at a very fundamental level. They provide a way for physicists to unveil hidden connections in nature, and have guided every branch of modern physics from quantum field theory, to the understanding of black holes, to the prediction of new particles including the Z and Higgs bosons.

"We use the ideas of symmetries corresponding to conservation laws pretty much all the time, but we don't immediately think 'Noether!'" Gregory says.

*

Following Noether's astounding breakthrough, Hilbert tried to secure a paid position for her at the University of Göttingen. The best he could do was to bring Noether in as an unpaid assistant, with her lectures billed under Hilbert's name. She didn't get an official position until 1919, after Einstein and others lobbied on her behalf, and it was only in 1922 that she began receiving a small income for her work.

Yet she was not prone to bitterness. She was at her happiest doing mathematics, her life-long love. Historical accounts paint a picture of a woman who would get so animated talking about mathematics, she didn't notice her blouse becoming untucked or wisps of her hair flying here and there in the classroom. She was totally unconcerned with looks or worldly possessions.

As Hitler rose to power in 1933, the dark clouds gathering in the world outside impinged on her life of pure mathematical ideas. Anti-Semitism in Germany intensified and it became dangerous to be a Jewish professor. Noether was one of the first teachers to be dismissed, because she was a Jewish pacifist.

Yet she worried more about others than for herself. Hermann Weyl, another German mathematician and a theoretical physicist, later wrote that "her courage, her frankness, her unconcern about her own fate, her conciliatory spirit, was, in the midst of all the hatred and meanness, despair and sorrow surrounding us, a moral solace."

Noether, like Einstein, went to the United States, where she had secured a position at Bryn Mawr College in Pennsylvania. According to a memorial address by Weyl, this was a happy period of her life and she felt deeply appreciated as never before.

Just 18 months later, on April 14, 1935, she died of complications following surgery to remove an ovarian cyst. She was 53.

Unlike Einstein, Emmy Noether never became a household name, perhaps because she was a mathematician rather than a physicist. Today, Noether is usually only encountered by students tackling her theorems in university math classes.

"I think, relative to the importance of her contribution, she is less of a 'star.' Why? Maybe because she proved a theorem, and physicists are less into theorems," Gregory says.

Yet Noether not only changed the course of modern physics, she opened the doors to physics and mathematics for women around the world.

"By being excellent, genuinely excellent, she showed that you did not have to be a man to prove a good theorem or to start a new area of mathematics. It was some time before things began to open up, but she showed that it could be done," Gregory said.

"She changed the world she lived in and she changed it for the better and for all of us."

– Rose Simone

KEEP CALM AND CARRY ON RESEARCHING

How one woman is dealing with, and helping address, inequality in physics.

Energy can neither be created nor destroyed, but it can, Sarah Shandera has discovered, be wasted.

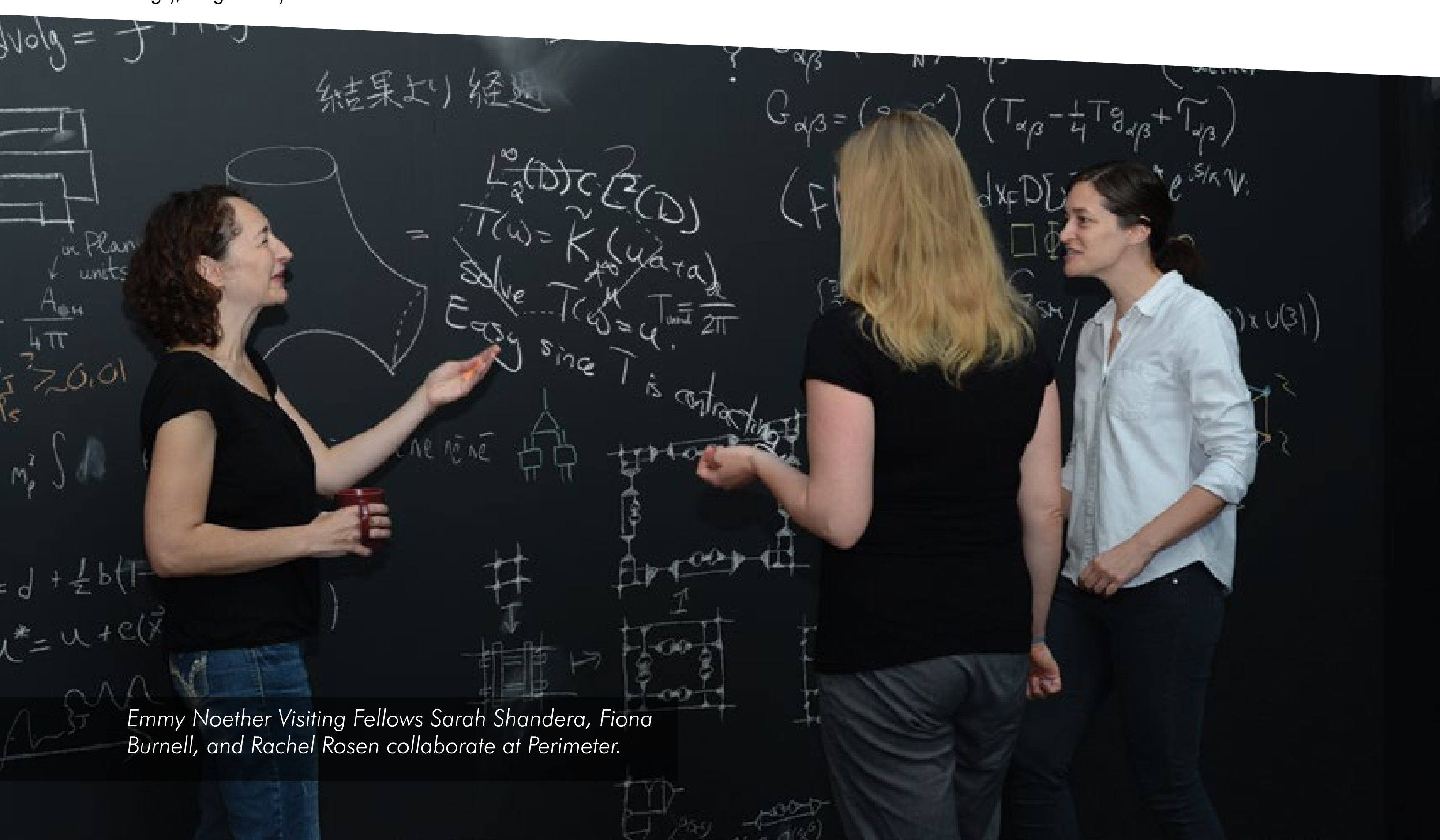
As a woman in what is largely a male game, the theoretical physicist has been spoken over, condescended to, ignored, vastly outnumbered, and burdened with a responsibility to represent all women.

That's not the whole story, she's quick to point out. She's received a lot of encouragement along the way. But when faced with the field's lingering inequality, the researcher finds herself with two options: get angry, or get busy.

"For women, there's often a small sense you don't belong. And that's stupid, because it's a drain on your resources and you'd do better physics if you didn't have that drain," she says.

This is her second stint at Perimeter. After doing a postdoc here from 2009 to 2011, she has returned as an Emmy Noether Visiting Fellow, taking a semester's break from her assistant professor duties at Penn State.

Like many of the women slowly evening the scales of physics participation, Shandera is a success. But it has taken her a while to feel like one.



Emmy Noether Visiting Fellows Sarah Shandera, Fiona Burnell, and Rachel Rosen collaborate at Perimeter.

Shandera is from Montana, with no family history in academia. Her parents were always supportive of her educational aspirations, but as a teen she faced backlash from others simply for liking math.

She worked hard to defy the doubters. Math led to physics, and, at the University of Arizona, a mentor guided her towards grad school. After attending a number of conferences, Shandera found cosmology. It was mathematically challenging but constrained by data, a tension she found appealing.

Today, she studies the primordial era of the universe and the theory of inflation.

"The interesting part for me is helping test our theory with observations. I'm interested in the theory, but then you have to do numerical work to turn it into predictions for galaxies, and then look at actual data," she says.

Wanting to devote more time to speculative new avenues of exploration, Shandera applied for an Emmy Noether Visiting Fellowship, an annual program that brings early- and mid-career scientists to Perimeter for research and collaboration. Shortly after applying, she found out she was pregnant.

What could have been a stumbling block elsewhere was a mere detail change at Perimeter. The Institute arranged for family accommodation and daycare for her 15-month-old daughter. Her husband, physicist Louis Leblond, was awarded a fellowship by Penn State to develop online physics courses, which he's doing in Waterloo.

Shandera is happily "gorging on new ideas," and not just with fellow cosmologists. Other specialties, such as particle physics and numerical physics, are coming up with ideas and tools that could help cosmologists solve some of their most vexing puzzles: the veracity of inflation, the make-up of dark energy, the nature of black holes.

"There are a lot of people here with interesting ideas in a lot of those directions," Shandera says.

That's why she feels Emmy Noether Fellowships and programs like it are so valuable to physics.

"Science is a very social thing. Belonging is really important. You get so much stuff done, other people are excited, and you learn things. When you see other people make it, you feel less this weight of people saying women can't do it. Here I am. I worked hard. You can do it too."

– Tenille Bonoguore

Using Noether's theorems, physicist seeks to modify gravity theory

Rachel Rosen is working to modify Albert Einstein's 100-year-old gravitational theories in order to understand the accelerated expansion of the universe. The mathematical tools she's using are also 100 years old, and were developed by Emmy Noether.

"[Noether's theorem] is a beautiful and elegant theorem that can tell us so much about physical systems," says Rosen, an assistant professor of theoretical physics at Columbia University in New York and an Emmy Noether Visiting Fellow at the Perimeter Institute.

Rosen's research is in the applications of quantum field theory to particle physics, gravitational physics, and condensed matter systems. Most recently, she has been working on "massive gravity," an approach that gives mass to gravitons, the hypothetical particles thought to be responsible for mediating the force of gravity.

Giving gravitons mass may be a way to modify general relativity at the very large cosmological scale and provide a possible explanation for the accelerated expansion of the universe.

"It is not clear weather massive gravity is going to be able to address these issues or not, but we are hoping that, if it is not massive gravity, then maybe some related theory will lead us to some insight into this problem," Rosen says.

In 1915, Noether couldn't even get a paid position at the University of Göttingen in Germany because of her gender. Things have changed a lot in 100 years, but women are still underrepresented in physics. Perimeter's Emmy Noether Initiatives aim to address that imbalance through educational and research support for women and girls at all levels of science learning and research.

Being an Emmy Noether Visiting Fellow is "a fantastic experience," Rosen says, adding that it gives her the ability to really focus on the research. "It is a great opportunity to be interacting with so many people without being constrained by the usual responsibilities that I have."

And there's a benefit for science, too: "It is important for anybody to know that physicists are diverse and that they can become a scientist if they want to, regardless of what they look like," Rosen says.

– Rose Simone

EMMY NOETHER CIRCLE

Perimeter's Emmy Noether initiatives are supported by the Emmy Noether Council, a group of leaders from the corporate and philanthropic sectors who provide expertise to help guide and fund these efforts.

Council members are:

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Further Exploration: Watch cosmologist Ruth Gregory's lecture on Emmy Noether and her legacy, and a deep exploration of Noether's theorems by Peter Olver, both delivered at Convergence: **perimeterinstitute.ca/convergence**

Applications for the 2016 Emmy Noether Visiting Fellowships close January 10, 2016. For information, visit **perimeterinstitute.ca/emmy-noether-visiting-fellowships**

For more information about the Emmy Noether Circle, please contact Maria Antonakos at **mantonakos@pitp.ca**

Perfecting Math Without Numbers

As the newly announced Clay Riddell Paul Dirac Chair in Theoretical Physics, Pedro Vieira is continuing his quest to equip young researchers with the tools for success in analytics.

Pedro Vieira uses computers to aid in physics calculations – specifically, in the kind of calculations that don't involve numbers.

It sounds like a paradox – calculations without numbers – but it's not. Physicists often have a mathematical model and want to understand its behaviour better. The gold standard in physics is to take the analytical (as opposed to the numerical) approach: using mathematical techniques to derive the solution. For example, deriving Kepler's laws of planetary motion from Newton's law of gravitation is an analytical exercise: at no point do you need to know the mass or speed or distance of any particular planet. You can create a set of equations that describe any orbit, using only mathematical tools.

But what happens when the mathematics becomes so complex that even all the chalkboards at Perimeter can't contain it?

This is the realm in which Pedro Vieira works. Vieira is on a quest to find exact, or analytical, solutions in four-dimensional quantum field theory. This challenge has bedevilled researchers since the 1970s, and is probably the toughest and longest-standing set of problems in the field.

Vieira was still a PhD student when he and collaborators found the very first exact solution to a 4D quantum field theory. It was such an outstanding breakthrough, from a young person with such clear promise, that Perimeter made an almost unheard of move: offering Vieira a faculty position straight out of his PhD program.

That was six years ago, and it's certainly paid off. Vieira has made tremendous scientific progress toward a richer conceptual and practical understanding of 4D quantum field theory, which is the language in which particle physics, condensed matter physics, and much of cosmology is written. In recognition of his work, he's won a Sloan Research Fellowship and a Gribov Medal – top awards for young researchers.

Here at Perimeter, Vieira was recently appointed the Clay Riddell Paul Dirac Chair in Theoretical Physics. (Its namesake, Paul Dirac, was a remarkable young physicist who developed some of the first working laws of quantum mechanics.) The new chair has been generously funded by the Riddell Family Charitable Foundation, based in Calgary.

As Chair, Vieira is continuing a years-long effort to equip other young researchers with the tools to pursue analytical work. Like many physicists, Vieira uses software called Mathematica to streamline and organize his calculations. It still requires both mathematical talent and physical insight to follow the flow of ideas up and down the dimensions and through the different theoretical lenses, but Mathematica keeps the tremendously long calculations from tangling up, preventing near-inevitable human error. For a certain brand of theoretical physicist, learning to use a tool like Mathematica is an essential, career-changing skill, yet it's not widely taught. Young physicists are largely left to pick it up as they go along.

Vieira set out to change that. While still a student in Portugal, he founded the Mathematica Summer School on Theoretical Physics. When Perimeter offered him a position, it also agreed to sponsor and nurture the school. The school, which travels to broaden its reach, this year returned to Perimeter for its seventh event.

Attendees – typically PhD candidates in physics – spend each morning in lectures discussing advanced topics, then tackle real problems using Mathematica each afternoon. Wolfram, the software developer behind Mathematica, sends a senior developer to the school as an instructor and on-site resource.

"It's about streamlining analytical calculations – performing them without mistakes, and not being afraid of the long calculations. It's about becoming super-powered as a calculator," Vieira says.

This year's topic was entanglement. Perimeter Faculty member Guifre Vidal spoke about tensor networks, which he pioneered, and which are now everywhere in both condensed matter physics and quantum information. Juan Maldacena discussed "entanglement in the sky" – how quantum correlations affect what we see in the cosmic microwave background and provide a window into the evolution of the universe. Horacio Casini talked about entanglement entropy, which is a hot topic in string theory.

For Vieira, the real value of the Mathematica Summer School is shown in the acknowledgment section of new papers, as the school's graduates put their new skills to use. And with graduates beginning to come of age as researchers, we are seeing the effects of the training ripple outward, just as Vieira's own research career reaches a new stage of maturity as the Clay Riddell Paul Dirac Chair.

"The main thing is not to crunch big numbers," says Vieira. "It's about doing things that you can do with pen and paper, but much more efficiently."

– Erin Bow

Hunting for Common Ground

Few mysteries are bigger than the nature of the universe. The base facts are clear – the universe exists, and it is governed by rules we generally understand – but the deeper 'how' and 'why' remain tantalizingly out of reach.

Unlike in a cinema, where the audience sits in a darkened room waiting for the next clue to be disclosed, the people glued to this mystery must discover, then decipher, the clues themselves.

Still, when you're focused on the intrigue, it can be easy to forget there is someone sitting in the next row.

For five days in June, Perimeter Institute hit pause and threw up the house lights to hold Convergence, a gathering of 240 theorists, experimentalists, and alumni from 17 countries.

Part conference, part reunion, Convergence dismantled disciplinary and generational boundaries in a bid to uncover, and potentially solve, shared puzzles.

"These are amazing times for physics," said Perimeter Director Neil Turok as he opened the conference on June 22.

Physics, he said, faces a remarkable simplicity in the laws that seem to govern the universe at its small and large extremes, with a lot of interesting complexity in the middle. But it has been incredibly difficult to find cracks in those laws, the weak points which can be pried open to reveal new avenues of investigation and knowledge.

That might be about to change. "Many of us believe physics is poised for a new revolution."

The interplay of theory and experiment quickly emerged as a recurring touchstone throughout the lectures, panels, roundtables, and occasionally feisty question periods.

From the hunt for gravitational waves to the use of ultra-cold atomic clocks as a test-bed for theoretical ideas, experiment and theory are alternately sharing the lead.

For Perimeter particle physicist Natalia Toro, whose work has helped shape the practice of experimental particle physics, the smallest scales "overwhelmingly tell us we need to be asking more questions."

Theory and experiment are butting up against unknowns, and the path forward demands a new approach. "Exploratory experiments that are practical and relevant are much harder to come by now," Toro said. "This is where theory and experiment working together form a formidable team."

As the conference progressed, scientists grew more willing to speculate and make predictions about the future of physics.

Immanuel Bloch, scientific director of the Max Planck Institute for Quantum Optics, and Savas Dimopoulos, a Stanford University particle physicist who is also a Distinguished Visiting Research Chair at Perimeter, both predicted a big future in small experiments which can be more quickly and readily tied to theory.

For Bloch, whose work with ultra-cold atoms is revealing unprecedented glimpses into the quantum realm, the excitement lies in many fields coming together. Small-scale experiments have the advantage of being nimble and flexible, allowing researchers to change the initial conditions without the constraints of observation. "I think people should be more open to those experiments. They're having a hard time getting seen and getting funded."

With lectures deliberately aimed at a general physics audience, there was a sustained air of discovery as experts in one field were introduced to the latest ideas and challenges in many others, from the hunt for exoplanets and gravitational waves to the potential parallels between strange metals and black holes.

In this environment, "I don't know" was not just an acceptable answer. It was the most exciting answer.

"That's how new ideas can germinate across fields," said Nergis Mavalvala, an astrophysics professor at MIT. "Maybe we can talk about how something manifests in their experiments, versus in mine, and maybe there'll be some common ground."

Convergence didn't reveal the nature of the universe, but it never intended to. Instead, it pulled back the curtain to reveal a bigger picture, and offered some promising avenues of joint exploration.

– Tenille Bonoguore

Presenting Sponsor

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Thanks to the many sponsors and volunteers that made Convergence happen.

DISCOVERY

"There are a huge number of unsolved problems we can think about in physics. You also have all these problems we don't even know are out there waiting to be solved."

– Nergis Mavalvala, MIT

INNOVATION

"The work that's taking place here is going to translate itself into very tangible outcomes for all of humanity and society, and that's why this conference is so important."

– Bill Downe, CEO of BMO Financial Group

IMAGINATION

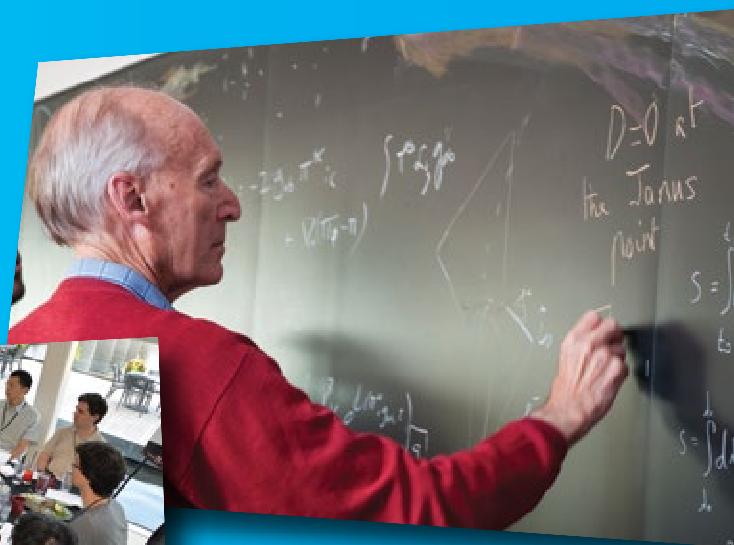
"There's just a tremendous amount of excellent young people driving forward the field, bringing new ideas."

– Immanuel Bloch, Max Planck Institute for Quantum Optics

COLLABORATION

"It's clear that you can see all kinds of discussions going on in the corridor of the latest topics in physics, which is just what you hope would happen at a conference like this."

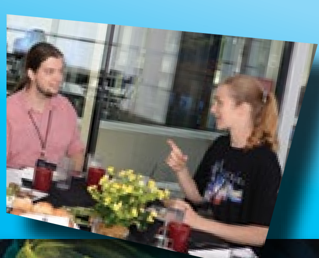
– Art McDonald, 2015 Nobel Laureate in Physics, Perimeter Board member

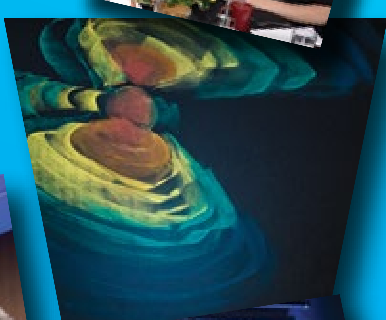


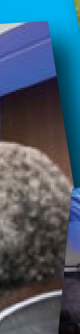
REUNION

"I had almost forgotten what it's like to see equations written the walls everywhere. It's that kind of playfulness with science that reminds me of when I first came here."

– Maita Schade, Perimeter Scholars International class of 2011







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The Living Chalkboard

Alexa Meade toys with perception and understanding as Perimeter's first artist-in-residence.

Chalkboards are ubiquitous at Perimeter Institute. Down every hallway, in every lecture hall and cozy nook, they offer a constant invitation for researchers to hash out vexing questions about the workings of the universe.

But on this autumn afternoon, a new and peculiar chalkboard is commanding more attention than the others. A murmuring crowd has formed around it. Cameras flash.

This one challenges not just the brain of the observer, but the intuition as well.

This chalkboard looks back at you. And then it blinks.

This tableau is the handiwork of Alexa Meade, a California-based painter and, for 10 days in September, the inaugural participant in Perimeter Institute's Coalescence Artist-in-Residence program.

The eerie blinking eyes belong not to Meade but to her two subjects, Lauren Hayward Sierens and Laurent Freidel, who blend almost seamlessly into the chalky landscape.

Meade has painted the Perimeter physicists from head to toe – clothing, hair and all – with shades of black and grey. The muted colours and smudges almost perfectly match the three-dimensional chalkboard that surrounds them: a half cube with two walls and a floor, chalked in calculations over the past week by Perimeter scientists.

With a chameleon-like transition, her subjects become part of a living diorama.

By painting her subjects "into" their mathematical environment, Meade has created a startling, perception-bending illusion. Her living, breathing, blinking subjects seem to flatten from three-dimensional people into two-dimensional portraits.

"I love artwork that totally plays with your sense of dimensionality and perception," says Meade, who has exhibited work in galleries around the world.

"I was contacted by Perimeter Institute to be artist-in-residence in part because of my play with dimensionality, and because a lot of the researchers are looking into the fourth dimension and higher dimensions."

Though Meade claims no expertise in theoretical physics, she arrived at Perimeter armed with insatiable curiosity, an outgoing personality, and the freedom to ask anyone anything. Well before she began work on her immersive chalk-art piece, she had coffee with researchers, joined interdisciplinary collaborations, and simply watched physicists do physics. She led a painting workshop during one of Perimeter's regular family nights, encouraging the children of researchers – and researchers themselves – to get creative and messy.

Suzanne Luke, curator of the artist-in-residence program, says Meade's "fearlessness" was vital to the project: "She's not one to shy away from asking questions, which created a wonderful synergy between the creative and scientific thought processes."

To create a work of art that immerses people in their surroundings, Meade says she must first try to understand those people and surroundings.

"There's so much genius, so many extraordinary minds working together here," she says. "I'm just listening, absorbing, and trying to ask questions that are provocative. That does force the scientists to actually rethink a lot of their foundations."

One of those scientists is Laurent Freidel, a long-time Perimeter faculty member whose own research often explores extra dimensions, and who volunteered to become one of Meade's living portraits. During the week prior to getting slathered with paint, Freidel chatted frequently with Meade about art and science, and the unexpected parallels between them.

"When you're a physicist, you understand that there is a fundamental difference between what you experience with your eyes…and what the world is really about," he says. "I think [Meade's] art presents this discrepancy between what you experience and what things are about."

Freidel and Hayward Sierens, an associate graduate student at Perimeter, sat unmoving for hours, in full view of their colleagues, as Meade painted them into their surroundings and then photographed the result.

Hundreds of pictures later, they emerge to clean themselves off. Meade's three-dimensional chalkboard will be dismantled; it was never intended to be a permanent piece. Like all of the chalkboards at Perimeter, it represented a snapshot of a fleeting collaboration, to be wiped clean to make way for new ideas.

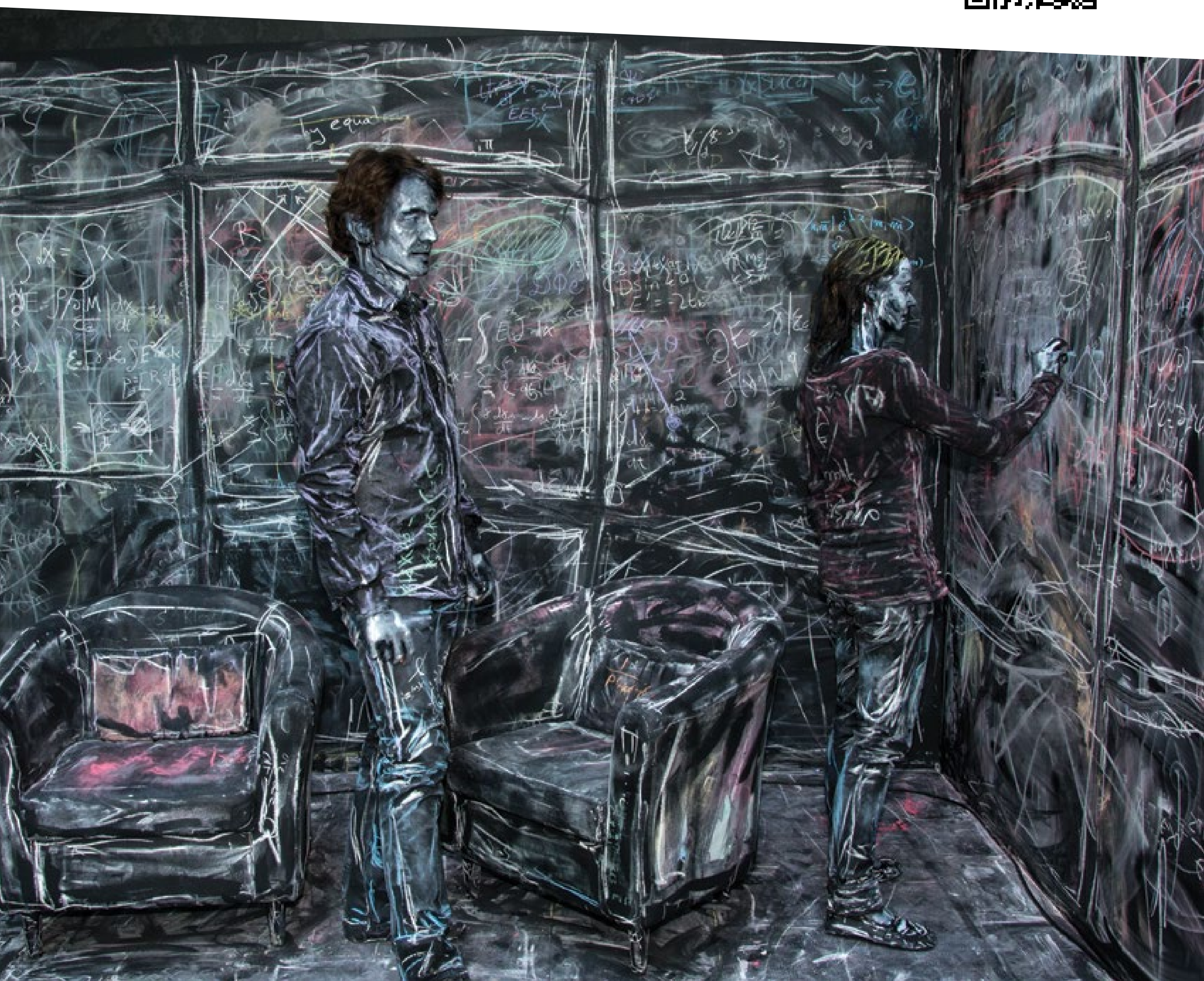
For Meade, this notion of impermanence was an important aspect of her residency at Perimeter. It highlighted that ideas and perceptions are alive – and they are most alive when we challenge them.

"Art is one way of interpreting the world," says Meade. "Physics is another. I don't think they need to be separate. I think they can work together for unlocking some of the mysteries that surround us."

– *Colin Hunter*

Further Exploration: Watch "The Living Chalkboard: Alexa Meade at Perimeter" and other PI videos at www.youtube.com/PIOutreach

Scan to see the photo gallery of Meade's living installation at Perimeter:



A New Lens to View Quantum Gravity

In 1973, Jacob Bekenstein, then a 25-year-old graduate student finishing up his PhD at Princeton, came up with a radical proposal that black holes should have intrinsic entropy. His surprising suggestion hinted that these pristine solutions of Einstein's theory of gravity carried an enormous but unseen microscopic complexity. While his idea originally met with strong opposition, this melted away two years later with Hawking's discovery that black holes emit (nearly) thermal radiation. The Bekenstein-Hawking formula for the entropy of a black hole is now widely regarded as one of the most remarkable discoveries in fundamental physics.

Interestingly, way over in information theory, entropy also plays a central role; for example, it measures the average number of bits needed to store one "letter" of a message. Recently, Bekenstein's and Hawking's discoveries have been recognized as the first clues of profound connections between information theory – in particular, its modern incarnation as quantum information theory – and gravity.

In essence, quantum information theory can, in some instances, function as a lens, providing methods and tools for solving problems in quantum gravity that would otherwise be very difficult or intractable. For this reason, many theorists looking to unify the geometry of general relativity with the indeterminacy of quantum mechanics are turning to quantum information for insight. Recently, remarkable progress has been made in this direction using holography (*Editor's note: See the accompanying article "Gravity in a Hologram" on page 14.*)

The Quantum Information in Quantum Gravity workshop, held at Perimeter from August 17 to 21, was the second in a series aimed at examining recent developments, and facilitating interactions between the quantum information and the quantum gravity communities, as well as researchers with common interests studying condensed matter physics and quantum field theory.

This edition of the workshop featured a broad range of talks and an energetic and enthusiastic atmosphere, with a good mix of students, postdoctoral researchers, and senior researchers among the 65 participants. This certainly seems to point to an exciting future for this research program.

The dates of the meeting were coordinated with the Mathematica Summer School on entanglement, which was hosted at Perimeter the following week. Many of the younger researchers stayed on to attend the school, while some of the more senior researchers served as lecturers.

There was a bittersweet symmetry to learning, on the meeting's first day, that Jacob Bekenstein had just passed away. It was, on the one hand, profoundly sad to hear news that we had lost a true pioneer, but on the other, our meeting was itself a reminder of how the seeds he planted so long ago have taken hold and flourished in the intervening years. We dedicated the meeting to him, and, hopefully, planted new seeds that will bear fruit in the years to come.

– Robert C. Myers

Other Recent Conferences

RECENT PROGRESS ON HIGH TC SUPERCONDUCTIVITY AND RELATED PROBLEMS

July 6-10 | Watch the talks: pirsa.org/C15036

An apparent quantum complexity arising from strong electron correlations and Mott physics, in the form of new experimental results, continues to challenge theorists exploring high temperature superconductivity in cuprates. This workshop addressed current challenges, and sought some simplicity and new physics behind the complexity.

◀ *Faculty member Guifre Vidal and Juan Maldacena discuss tensor networks at the Mathematica Summer School.*

2015 TRI-INSTITUTE SUMMER SCHOOL ON ELEMENTARY PARTICLES (TRISEP)

July 6-17 | Watch the talks: pirsa.org/C15032

This was the first time TRISEP (a partnership between PI, TRIUMF, and SNOLAB) has been hosted at Perimeter, and it attracted close to 50 graduate students from Canada, the United States, and abroad. Five lectures a day addressed Standard Model and Beyond the Standard Model physics, astroparticle physics, cosmology, and modern amplitude techniques.

COSMIC FLOWS (AND OTHER NOVELTIES ON LARGE SCALES)

August 10-12 | Watch the talks: pirsa.org/C15035

Young researchers and experts worked to identify the most significant scientific questions facing observational cosmology, and to discuss the promise of observational probes as the field's attention shifts to the next frontier of Large Scale Structure research.

Support for this workshop was provided by CITA.

THE UNRUH FEST: A CELEBRATION IN HONOUR OF BILL UNRUH'S 70TH BIRTHDAY

August 13-14 | Watch the talks: pirsa.org/C15039

Faculty member Laurent Freidel and Nobel Laureate Gerard 't Hooft at the Information Theoretic Foundations of Physics conference.

MATHEMATICA SUMMER SCHOOL

August 24-29 | Watch the talks: pirsa.org/C15040

This seventh installment of the travelling summer school focused on entanglement. Speakers included Juan Maldacena, Horacio Casini, Guifre Vidal, and summer school founder Pedro Vieira.

NON-COMMUTATIVE GEOMETRY AND PHYSICS

September 12 | Watch the talks: pirsa.org/C15061

Mathematicians, cosmologists, and quantum gravity researchers gathered for a day of talks and discussion on non-commutative geometry and its connections to particle physics, quantum gravity, and cosmology.

Support for this workshop was provided by Gauge Theory as an Integrable System (GATIS) and Perimeter's Tensor Networks Initiative.

RENORMALIZATION IN BACKGROUND INDEPENDENT THEORIES: FOUNDATIONS AND TECHNIQUES

September 28-October 2 | Watch the talks: pirsa.org/C15064

This workshop balanced general and technical issues of renormalization, with discussions on numerical tools, analytical approaches, and conceptual questions, and presentations from quantum gravity researchers as well as computational physicists and condensed matter/quantum information researches.

CONDENSED MATTER PHYSICS AND TOPOLOGICAL FIELD THEORY

October 21-24 | Watch the talks: pirsa.org/C15070

Recent developments in topological field theory were discussed and probed for potential research use by mathematicians and high-energy physicists, with a particular focus on the classification of symmetry-protected topological phases of matter, the study of SPT phases with fermions, and the application of TFT to condensed matter.

Support for this conference was provided by The John Templeton Foundation

PI-UIUC JOINT WORKSHOP ON STRONGLY CORRELATED QUANTUM MANY-BODY SYSTEMS 2015

November 5-6 | Watch the talks: pirsa.org/C15071

The fourth workshop on condensed matter physics held jointly with the University of Illinois Urbana-Champaign since 2012, the workshop sparked discussion and collaborations in condensed matter physics, including topological phases, quantum field theories for condensed matter, and numerical methods.

Upcoming Conferences

FEEDBACK OVER 44 ORDERS OF MAGNITUDE: FROM GAMMA-RAYS TO THE UNIVERSE

March 14-16

DEFORMATION QUANTIZATION OF SHIFTED POISSON STRUCTURES

April 18-22

TIME IN COSMOLOGY

May 30-June 3

IT FROM QUBIT

July 17-30

Keep up to date with all Perimeter conferences at www.perimeterinstitute.ca/research/conferences-and-workshops

Dollar Store Demos

Make engaging science lessons from everyday objects? Anything is possible for EinsteinPlus teachers.

A foam dart with a suction cup is fired from a toy pistol. Someone honks a plastic bugle. A balloon bursts. Normally, one would expect a beleaguered teacher to silence this raucous group – but this is not a normal classroom.

"This is what you get when you put a bunch of physics teachers in a room together," says Arno Dirks, one of roughly 40 educators from around the world who opted to become students again to attend Perimeter's EinsteinPlus summer workshop.

For more than a decade, "EPlus" has immersed physics teachers in the deep end of modern physics, supplying them with hands-on tools and techniques to share cutting-edge physics with their own students.

Today, the teachers are frantically putting the finishing touches on their "Dollar Store Demos," a challenge to deliver three-minute science demonstrations using inexpensive household items.

Two days earlier, after a tour of the nearby Institute for Quantum Computing, the teachers were taken to a local dollar store, handed envelopes containing $10 per team, and told they had 20 minutes to spend that cash on things to make a fun, engaging physics lesson.

The result is a hodgepodge of stuff scattered around the classroom: a hula hoop, orange Play-Doh, marbles, plastic cups, laser pointers, toothpicks, cotton candy, and the like.

The first team uses a hockey stick, a metre stick, and a dustpan to find the centres of mass on objects of different shapes and sizes.

Ten more teams, at three-minute intervals, dash through their presentations in this fashion, demonstrating everything from wave amplitudes (using a rope and red plastic cups), to gravitational lensing (a laser fired through pouring water), to gravitational potential energy (a foam dart fired at a lightweight pendulum).

The teachers have come to know each other well over the preceding five days of workshops and collaboration sessions, so good-natured heckling abounds. When Chris Nichols, a high school teacher from Colorado, demonstrates the relationship between acceleration and air pressure by spinning like a figure skater while holding a lit candle, someone hollers, "Nice radius!"

The teachers burst into laughter, and Nichols, dizzily, joins in. This is exactly the kind of camaraderie and collaborative atmosphere that inspired her to attend EinsteinPlus for the second time.

"I was here before and, as a result of that experience, I turned my curriculum upside down and started infusing what I learned here," she says later. "I found it had a dramatic impact on my students."

The frenetic silliness of the Dollar Store Demos aside, the workshop tackles serious questions about learning and pedagogy, and gives teachers the tools and support they need to reach students who otherwise might have an aversion to science.

That's the driving motivation behind EinsteinPlus. Teachers leave equipped to share complex physics concepts – dark matter, curved spacetime, quantum theory – with students in ways that are interactive, fun, and meaningful.

Agne Junolainen, who travelled from Estonia to attend the workshop, describes it as an "amazing" experience that (almost) made her wish summer vacation were already over: "I can't wait to get back and rewrite my courses to incorporate these things into my classroom."

For Miles Hudson, a teacher from Durham in northern England, the most rewarding aspect of EinsteinPlus is knowing that it will benefit students at a pivotal point in their lives, when a spark of revelation about science might influence their future careers.

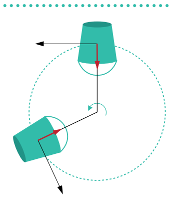
"Until you've actually been on the EinsteinPlus week, you cannot comprehend just how incredibly useful it will be directly in your classroom," says Hudson. "And I always tell my students that, with physics, you can explain anything. It's so powerful."

– Colin Hunter

Centripetal Force

Stuff you need:

- Plastic pail or bucket
- Sturdy rope
- 1 cup of water
- Courage!



What to do:

Attach the rope to the pail and pour in 1 cup of water. Make sure you've chosen a pail that is not too heavy. Hold the rope so the pail dangles around knee-height. Swing the pail in a circle overhead. Swing fast and water will seem to defy gravity!

What's the deal?

Why doesn't the water fall and soak you? The water wants to travel on a straight path as does the bucket, but the tension in the rope keeps them both turning in a circle.

PI PERIMETER INSTITUTE

Further Exploration: Watch "Physics Fast and Frugal" and other PI videos at www.youtube.com/PIOutreach

Scan here to download your own Dollar Store Demos.

Physics and Friendships Flourish at Summer Camp

The International Summer School for Young Physicists aims to inspire as much as educate.

A half-dozen oversized beach balls, each as plump as a prize-winning pumpkin, bounce about the classroom.

Like most beach balls, they practically beg to be volleyed by playful palms, and the students giddily oblige. Unlike most beach balls, these ones are about to illustrate one of the most mind-boggling and important discoveries in science.

"OK, folks," the teacher hollers over the commotion. "No more beach party. To fully explain Einstein's concept of gravity, we're going to adapt it to something that's curved."

Balls cease bouncing. Giggles quiet. This is what the students really came for: to learn some serious physics.

Forty teenagers from all over the world have gathered at Perimeter Institute for the annual International Summer School for Young Physicists (ISSYP) – a kind of two-week physics boot camp. The teacher is Kevin Donkers, an educational consultant at Perimeter who knows that physics is a subject best learned by doing.

This morning's session is about scientific models, and how various models can help us explain (or, in some cases, fail to explain) the phenomena we observe and experience. The beach balls have come into play to illustrate a thought experiment in which one person (Alice) falls off a ladder, with someone else (Bob) standing nearby.

Using strips of painter's tape and some arts-and-crafts prowess, the students bedeck the beach balls with perpendicular axes depicting time and space. They then place vertical strips of tape to depict the ladder reaching from the equator up to the north pole (just as they had done on the two-dimensional surfaces of their desks earlier in the lesson).

"This is the time axis," says 17-year-old Joscelyn van der Veen, applying a strip of the sticky green tape to the ball while her classmates hold it still. "We need to keep this axis straight – this is science!"

The big question: will the beach ball version reveal something different than the version on the surface of the desk? The answer, the students discover, is yes. Depicting the scenario on the ball shows that time should "tick differently," as Donkers puts it, at the top of the ladder than it does at the bottom.

This is revealed because, on the beach ball, the length of tape required to connect the tops of the ladders (that is, the amount of "time") is different than is needed to connect the bottoms of the ladders at the equator. Time elapses differently on the ground than it does atop a ladder.

This time dilation is a hallmark of Einstein's general relativity and is, among other things, what makes GPS technology work. The demonstration shows that Einstein's "acceleration" model helps explain something that another model, the "force" model of

Newton, does not (and the beach balls provide a handy depiction of curved spacetime).

For these students, some of whom have travelled from as far away as Tunisia and Singapore to attend the camp, such hands-on activities bring physics to life in ways that textbooks do not.

"I've always loved physics. I find it really fascinating not just to learn from the curriculums, but to extend that deeper and think about the more abstract concepts in the universe," says 18-year-old Kiri Daust from Smithers, British Columbia. "There aren't really many opportunities, at least in my high school, to do that."

It's a sentiment echoed by his ISSYP classmates, who sometimes struggle back home to find peers who share their passion for physics. "Here, you don't feel like an outsider if you are enthusiastic about physics or have other interests in science or math," says 18-year-old Kishan Makwana from London, UK. "This experience has definitely motivated me to pursue physics at university and beyond."

The two-week camp immerses students in all things physics – from quantum mechanics and cosmology to a trip deep underground at SNOLAB, a Canadian neutrino observatory. They receive mentorship from Perimeter researchers, work on team research projects, and experience the day-to-day workings of a theoretical physics research hub.

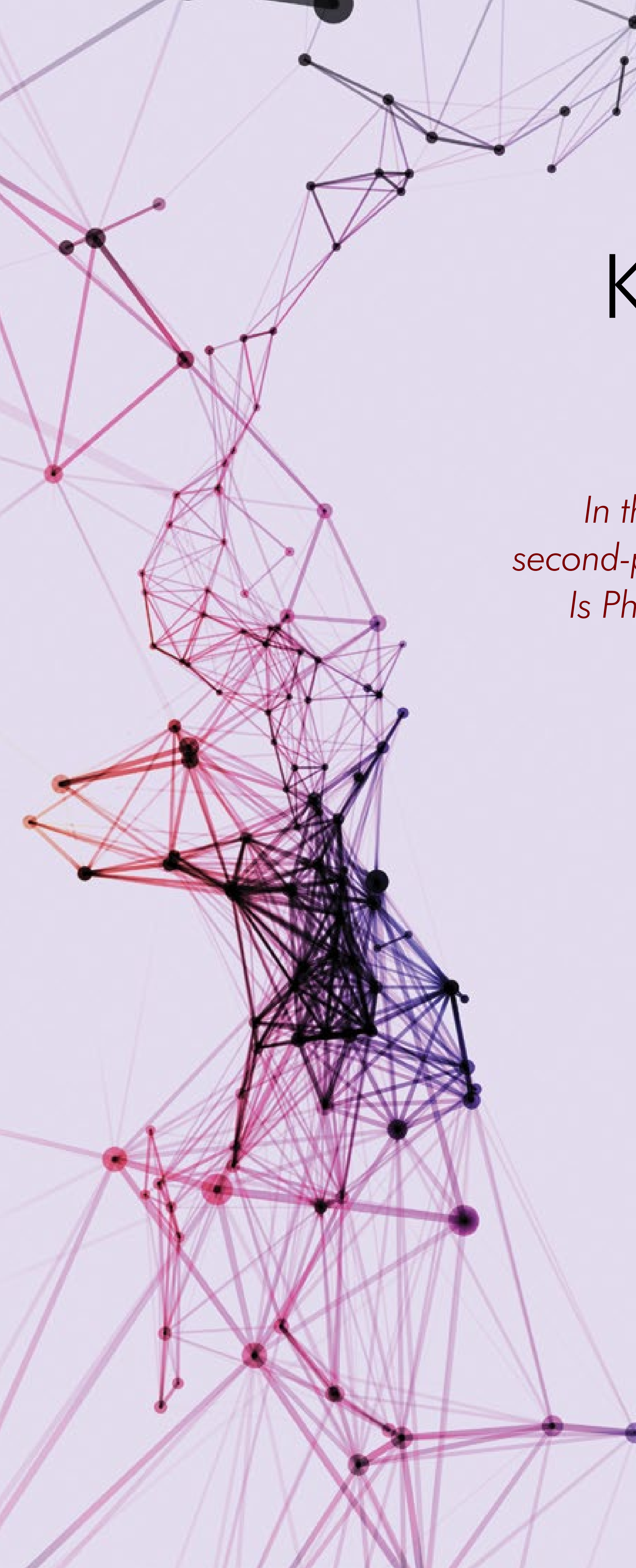
Offering such experiences to exceptional students, regardless of their financial or geographic situations, is only possible thanks to ongoing support from the RBC Foundation, which has donated $100,000 to the camp every year since 2011 and has committed to continue as Presenting Partner of ISSYP through 2017.

"Perimeter's programs for youth, teachers, and the public are seeding future generations of scientific thinkers," says Valerie Chort, RBC's Vice President of Corporate Citizenship. "Giving high school students the chance to learn about theoretical physics from working scientists in an environment like Perimeter is an outstanding opportunity that RBC is proud to support."

Many of the students who attend ISSYP are determined to pursue physics and mathematics in university, and ISSYP is structured to give them a leg-up in those pursuits. For others, though, the path ahead is still undecided. Regardless of where it takes them, ISSYP encourages students to think big and challenge themselves.

"I've learned how much I don't know, and I've realized that is not an obstacle," says 18-year-old Lola Hourihane of Dublin, Ireland. "It just encourages me to keep learning more. The best thing I've learned is what I'd call the physicist's outlook – to be motivated in the pursuit of knowledge."

– Colin Hunter



THE KNOWLEDGE NETWORK

In this abridgement of his 2015 FQXi second-prize-winning essay "Mathematics Is Physics," Matthew Leifer argues that mathematics is a natural science.

All our knowledge is human knowledge. It is discovered, organized, learned, and evaluated in an ongoing process by a social network of finite beings. This means that the structure of our knowledge will, in addition to reflecting the physical world, also reflect the nature of the process that generates it.

I do not mean to imply that human knowledge is merely a social construct – it is still knowledge about an objective physical world. However, to explain why abstract pure mathematics later shows up in physics, we must examine the motivations and methodology of those who develop it; find the hidden empirical tether in their methods; and how the patterns and regularities they create are patterns and regularities of nature in disguise.

It is common to view human knowledge as hierarchical. The various attempts to reduce all of mathematics to logic or arithmetic reflect a desire to view mathematical knowledge as hanging hierarchically from a common foundation. However, the fact that mathematics is now seen as having multiple competing foundations – logic, set theory, or category theory – indicates that something is wrong with this view.

Instead of a hierarchy, I am going to attempt to characterize the structure of human knowledge in terms of a network consisting of nodes with links between them.

Roughly speaking, the nodes represent different fields of study. We could draw a network wherein nodes represent things like "physics" and "mathematics," or we could add more specific nodes representing things like "quantum computing" and "algebraic topology." To avoid triviality, it should be set closer to the level of individual concepts than vast fields of study.

Next, a link should be drawn between two nodes if there is a strong connection between the things they represent. If it has occurred to a human being that the two things are strongly related – e.g., if it has been thought interesting enough to do something like publish an academic paper on the connection, and the connection has not yet been explained in terms of some intermediary theory – then there should be a link between the corresponding nodes in the network.

If we imagine drawing this network for all of human knowledge, then it is plausible that it would have the structure of a scale-free network.

This would explain why it seems so plausible that knowledge is hierarchical. In pursuing a university degree, one typically learns a great deal about one of the hubs, such as fundamental physics, and a little about some of the more specialized subjects that hang from it. As we get ever more specialized, we typically move away from our starting hub toward more obscure nodes, which are nonetheless still much closer to the starting hub than to any other hub.

Our local part of the network looks much like a hierarchy, so it is not surprising that physicists end up thinking that everything boils down to physics, whereas sociologists end up thinking that everything is a social construct.

In reality, neither of these views is right, because the global structure of the network is not a hierarchy.

The theory of theory-building

When a sufficiently large number of strong analogies are discovered between existing nodes in the knowledge network, it makes sense to develop a formal theory of their common structure, and replace the direct connections with a new hub, which encodes the same knowledge more efficiently.

Consider natural numbers and arithmetic. Initially, people noticed that discrete quantities of sheep, rocks, apples, etc. have properties in common. It therefore makes sense to introduce a more abstract theory that captures the common features, and this is where the theory of number comes in. This has the effect of organizing knowledge more efficiently.

Now, instead of having to learn about quantities of sheep, rocks, or apples, one need only learn about the theory of number and then apply it to individual cases as needed. In this way, the theory of number remains essentially empirical. It is about regularities that exist in nature, but are removed from our direct observations by one layer of abstraction.

Once it is established, the theory of number allows for the introduction of new concepts that are not present in finite collections of sheep. It develops its own internal life and is partially freed from its empirical ties.

Once several abstract theories have been developed, the process can continue at a higher level. For example, category theory was born out of the strong analogies that exist between the structure preserving maps in group theory, algebraic topology, and homological algebra. At first sight, it seems like this is a development that is completely internal to pure mathematics, but what is really going on is that mathematicians are noticing regularities, within regularities, within regularities … , within regularities of the physical world.

In this way, mathematics can become increasingly abstract and develop its own independent structure whilst maintaining a tether to the empirical world.

This is why abstract mathematical theories show up so often in physics: abstract mathematical theories are about regularities within regularities of our physical world; physical theories are about exactly the same thing.

The only difference is that whilst mathematics started from empirical facts that only required informal observations, physics includes the much more accurate empirical investigations that only became possible due to scientific and technological advances, such as the development of telescopes and particle colliders.

Possible Implications for Physics

I see two implications of my theory of knowledge and mathematics for the future of physics. Firstly, in network language, the concept of a "theory of everything" corresponds to a network with one enormous hub, from which all other human knowledge hangs via links that mean "can be derived from."

A scale-free network could have a hierarchical structure like a branching tree, but it seems unlikely that the process of knowledge growth would lead uniquely to such a structure. It seems more likely that we will always have several competing large hubs, and that some aspects of human experience, such as consciousness and why we experience a unique present moment of time, will be forever outside the scope of physics.

Nonetheless, my theory suggests that the project of finding higher-level connections that encompass more of human knowledge is still a fruitful one. It prevents our network from having an unwieldy number of direct links, and allows us to share more common vocabulary between fields and to understand more of the world with fewer theories.

Thus, the search for a theory of everything is not fruitless; I just do not expect it to ever terminate.

Secondly, my theory predicts that the mathematical representation of physical theories will continue to become increasingly abstract. The more we try to encompass in our fundamental theories, the further these hubs will be from our node of direct sensory experience. Future theories of physics will not become less mathematical, as they are generated by the same process of generalization and abstraction as mathematics itself.

Our direct empirical observations are the raw material from which our mathematical theories are constructed, but the theories themselves are just convenient representations of the regularities within regularities of the physical world. Mathematics is constructed out of the physical world rather than the other way round.

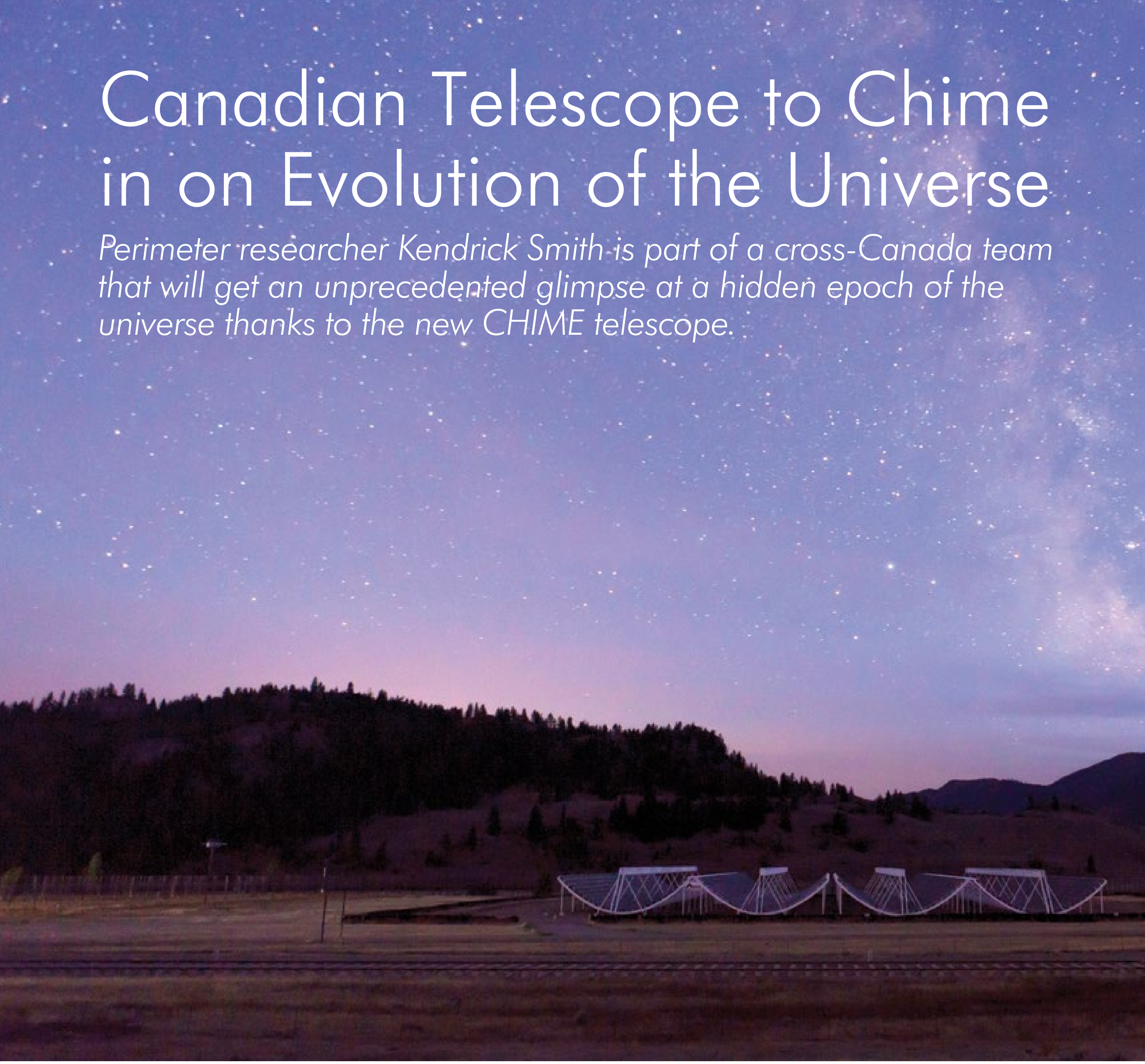
– Matthew Leifer is a long-term visiting researcher at Perimeter Institute.

The 2015 FQXi essay contest topic was "Trick or Truth: the Mysterious Connection Between Physics and Mathematics."

Scan here to read all the prize-winning essays.

Canadian Telescope to Chime in on Evolution of the Universe

Perimeter researcher Kendrick Smith is part of a cross-Canada team that will get an unprecedented glimpse at a hidden epoch of the universe thanks to the new CHIME telescope.



From a distance, it looks like a snowboarder's dream: four halfpipes, each 100 metres long, running side by side amid the Canadian Rockies.

A closer look, however, reveals a structure designed not to propel athletes into the air, but to propel science into uncharted places – or, more specifically, uncharted times – in the universe.

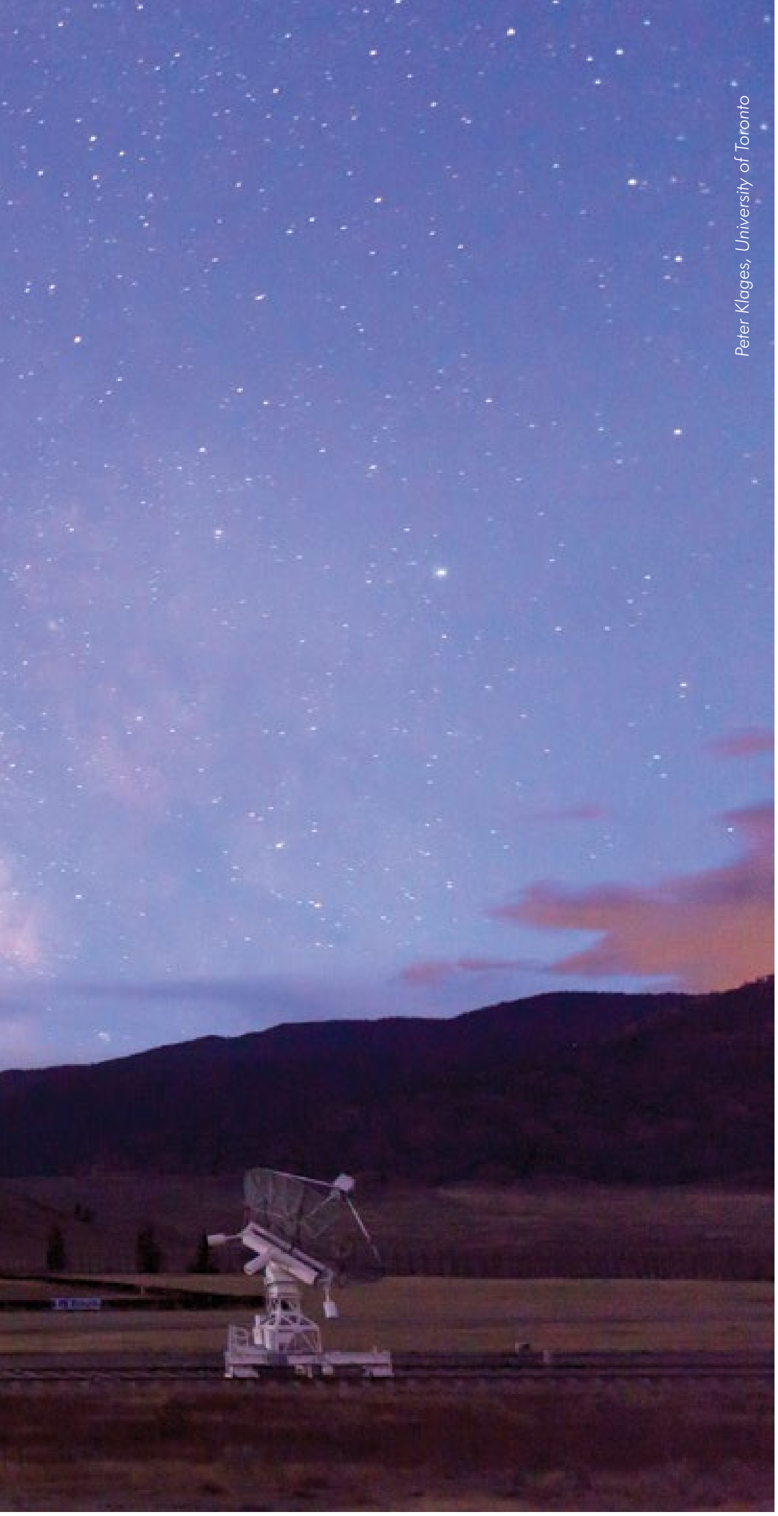
Just outside of Penticton, BC, nestled in a valley protected from radio wave disruption, lies the framework of the CHIME telescope, which will soon begin scanning the sky in search of clues about the evolution of the cosmos.

The CHIME acronym stands for the Canadian Hydrogen Intensity Mapping Experiment, which explains much about *what* the telescope is looking for, but less about *when*.

CHIME will gaze at the adolescent universe, the middle period when the personality of the cosmos was, like that of any typical teenager, a bit mysterious.

Whereas the newborn universe of 14 billion years ago is quite well understood (thanks to the cosmic microwave background imprinted on the sky shortly after the big bang), and the more recent universe is within the reach of many experiments, the adolescent universe has remained hidden from view.

"The in-between period is actually very difficult to access," says Perimeter Institute cosmologist Kendrick Smith, who is working on the CHIME project alongside researchers from the University of British Columbia, the University of Toronto, McGill University, and the Dominion Radio Astrophysical Observatory.


Peter Klages, University of Toronto

Probing this in-between era of the universe – roughly a few billion to 10 billion years after the big bang – has the potential to uncover important clues about one of the most puzzling problems in cosmology: the acceleration of the universe.

This acceleration, which slowed right after the big bang, picked up speed again during the adolescent era, when the effects of dark energy seem to have begun taking hold.

By measuring the distribution of neutral hydrogen in distant galaxies (a technique called intensity mapping), CHIME may glimpse the period in cosmic history when this speed-up occurred, allowing researchers to sleuth out some fundamental answers about why our universe is the way it is.

"At the end of a long chain of steps, we're trying to answer some really fundamental mysteries of physics," says Smith. "How did the big bang happen? What is the particle identity of dark matter? What new physics is responsible for the late-time acceleration of our universe?"

Until very recently, an experiment with the ambitions of CHIME would have been impossible because the technological horsepower needed to process the data it will collect simply did not exist.

That horsepower has come from a somewhat unexpected source: the video game industry. It turns out that the kind of co-processors required to blast marauding aliens on next-generation gaming consoles can, with minor tweaks, process the vast amounts of data that CHIME will collect when it becomes fully operational in the next couple of years.

"We've been waiting to get more powerful computers for a long time," says Smith. "It's such a big computing problem to analyze all the data."

When CHIME begins scanning the sky, it will process information in real time at a rate of approximately one terabit per second. That's roughly one percent of the processing requirements of the entire Internet – a staggering, unrelenting surge of information.

That's where Smith comes in. He describes himself as a "data-oriented cosmologist," and has made significant contributions to the collection and analysis of enormous data sets on the Planck Satellite and Wilkinson Microwave Anisotropy Probe (WMAP) projects to map the cosmic microwave background.

Smith and colleagues, including Perimeter Associate Faculty member Ue-Li Pen, will face a number of new challenges when it comes time to analyze the data streaming into CHIME – partly because of the sheer vastness of time and space the telescope will probe.

The telescope's unconventional design – the four side-by-side halfpipes – makes it particularly suited to such an ambitious project. While the telescope itself has no moving parts, it happens to be affixed to a very reliable piece of moving machinery: planet Earth.

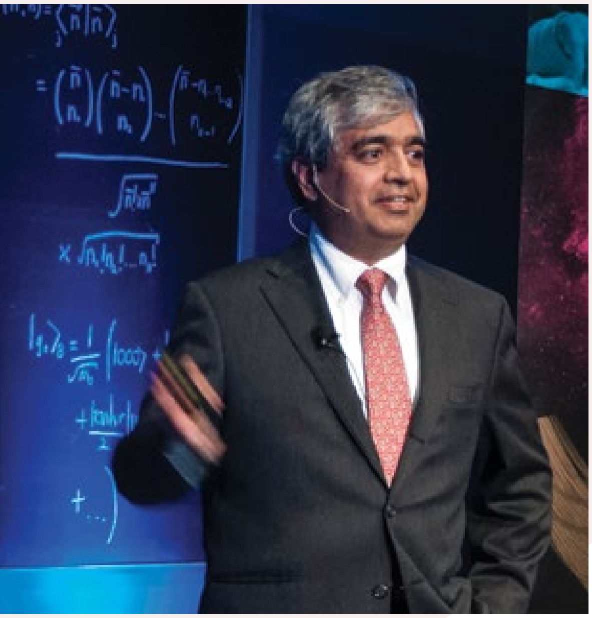
Every night, the rotation of our planet will sweep CHIME's curved, wire-mesh surface across a new swath of the cosmos, allowing it to pick up faint radio emissions from our universe's distant past.

Night after night, month after month, CHIME will amass enough information to map cosmic structure over the largest volume of the universe ever observed, with resolution sharp enough to discern 'baryon acoustic oscillations,' which are fluctuations in the density of matter in the universe that help cosmologists understand more about the effect that dark matter has on the accelerating universe.

Smith, with collaborators across Canada, will scour the data in search of the elusive catalyst that sparked the universe's accelerating expansion. For now, they must wait until CHIME's halfpipe reflectors are outfitted with the high-powered electronics that will complete its eye on the sky.

"It's a very exciting project," says Smith. "The most exciting thing would be if we measure the expansion history of the universe better than anyone else has – that we learn something really new and fundamental. But we don't really know where it will lead, and that's part of the fun."

– Colin Hunter



Research on the Road

It's been a busy fall for Subir Sachdev. He jetted to Australia to receive the Dirac Medal for the Advancement of Theoretical Physics on September 1, then headed to Calgary in October to meet supporters at Cenovus Energy who funded his Perimeter Research Chair.

During both visits, the Harvard professor and Cenovus Energy James Clerk Maxwell Chair in Theoretical Physics at Perimeter Institute (Visiting) gave talks about his work on high-temperature superconductors, long-range quantum entanglement, and strange metals.

"Amazingly, there are deep connections between the properties of this mundane-looking superconductor and the properties of black holes," he said during the Dirac Lecture in Sydney. "That's allowing us to make progress in understanding quantum mechanics on large scales."

Harbir Chhina, Executive Vice-President of Oil Sands Development for Cenovus Energy, praised Sachdev's research, and encouraged other Canadian companies to support fundamental science. "Our company believes in innovation. We believe in fundamental research. The calibre of people at Perimeter is going to lead to advancements that will change our nation, change our world, and help us understand the universe better."

Max Metlitski Joins Faculty

Condensed matter researcher Max Metlitski joined the Perimeter faculty in October, coming from the Kavli Institute for Theoretical Physics at University of California, Santa Barbara, where he was a postdoctoral research associate. He completed his PhD at Harvard in 2011 under the supervision of Subir Sachdev. Metlitski's work has contributed to the theory of quantum criticality in metals and to the understanding of topological phases in the presence of interactions. In 2014, he won the William L. McMillan Award, which recognizes outstanding contributions by a young condensed matter physicist.

Perimeter Launches New Research Initiative

Physicists seeking to craft a theory of quantum gravity face a major challenge: the two theories they hope to unite don't talk to each other. The numerical tools currently at their disposal cannot bridge the divide between the quantum "discretuum" and the macroscopic "continuum."

Perimeter Faculty member Bianca Dittrich and Distinguished Visiting Research Chair Renate Loll are hoping to change this by establishing the From Discretuum to Continuum Research Initiative, in an effort to raise the level of numerical ability among physicists, and to help create a universal tool that can be applied to a number of proposed approaches to quantum gravity.

"You can do so much with good ideas," Dittrich said, "but many approaches get somehow stuck at this point. It would be good to have better tools."

Setting the Standard

Modern physics will soon become a significant part of the Saskatchewan high school physics curriculum, thanks in part to Perimeter Teacher Network member Karen Kennedy-Allin. As one of the lead writers for the Physics 30 curriculum update, which she presented at the provincial science and math conference, she is now piloting the coursework in her own classroom.

It from Qubit Collaboration

PI Faculty Chair Robert Myers is part of a new global collaboration funded by the Simons Foundation called It from Qubit: Quantum Fields, Gravity, and Information. The four-year collaboration, led by Stanford professor and Perimeter DVRC Patrick Hayden, brings together string theorists, computer scientists, and quantum information specialists with the aim to "use insights from quantum information theory and quantum computing to make progress on the deep question of reconciling the laws of quantum mechanics and of gravitation."

Life Meets Art for PI Researcher

Perimeter Faculty member Lucien Hardy gave theatre audiences a glimpse of physics life "behind the scenes" during a special event at the 2015 Stratford Festival. Three actors – Seana McKenna (centre), Scott Wentworth (centre right), and Tom Rooney (right) – performed a live reading of Michael Frayn's play *Copenhagen*, based on a meeting between Niels Bohr and Werner Heisenberg. After the reading, Hardy took part in a discussion and Q&A about the life of physicists, moderated by Stratford Festival Artistic Director Antoni Cimolino (left).

Getting the Goods at PI

When 50 global community leaders met in Toronto for the annual Intelligent Community Forum last summer, their first outing was a visit to the Region of Waterloo. Mayors and senior civil servants from cities, states, and regions around the world visited Perimeter to learn about the Institute's role in basic research and its links to the innovation ecosystem at local, provincial, and national levels. The group also visited the Waterloo Institute for Nanotechnology, Communitech, and other centres.

A World of Universes

Perimeter Director Neil Turok's book *The Universe Within* has been published in English, Italian, Korean, and Spanish, with a Japanese version to be released in December. Global editions from left: Canadian, English, Italian, Korean, English (alternate cover), and Spanish.

Student Award is a Poignant Win

It was particularly poignant when Sean Begy, a first-year science student at Queen's University, collected the Luke Santi Award for Student Achievement in November: Luke Santi, a passionate student and volunteer at Perimeter until his death in 2007, was Sean's cousin. "I think he would be so proud," Begy said of his cousin. "He's been my mentor since day one." The awards ceremony capped off a heady couple of days for Begy, who dined with Nobel laureate David Wineland after that night's public lecture, and a day earlier had bumped into Nobel laureate Art McDonald at the Queen's campus.

Inspired to pursue science by his cousin, Begy also excelled in tennis, volleyball, and basketball, competed in math and science contests, was an eager arts volunteer, and played a lead role in his high school play at Resurrection Catholic Secondary School in Waterloo. Now, as he plunges into university science with an eye to pursuing cosmology or particle physics, he says he once again feels like a child facing a world of possibility. "There's no turning back. It's my path."

Scholarship Supports Indigenous Researchers

Perimeter offered scholarships to attend Convergence to young researchers who identify as First Nations, Métis, Inuit, Native American, or Alaskan Native. Among the scholarship recipients was Theodore Halnon, a physics and mathematics undergraduate at Penn State University. "It really has been a career-changing and life-changing event," said Halnon. "Coming to Perimeter, my intentions were to expose myself to new areas of research – and I was extraordinarily successful. I was able to fill a notepad with potential future research topics."

CBC Ideas Visits PI

How important is imagination in physics? The CBC Radio Ideas team was on location at Perimeter during Convergence to record a two-part series, "Similes and Science," with cosmologist Matthew Johnson, exoplanet hunter Sara Seager, string theorist S. James Gates Jr., and PSI graduate Sonali Mohapatra. You can listen to the podcasts on CBC.ca/radio/ideas.

In Royal Company

Congratulations to Perimeter Science Advisory Committee Chair and DVRC Renate Loll, who was installed as a member of The Royal Netherlands Academy of Arts and Sciences in September. She is one of 16 new members, all of whom were nominated by peers from within and outside the Academy.

Celebrating the Sixth Class of PSI

Last June, in a ceremony filled with laughter and a few tears, 33 students from more than a dozen countries celebrated the completion of this year's Perimeter Scholars International (PSI) master's program.

At the graduation ceremony, held during Convergence, PSI classmates commemorated an intense year of physics, friendships, and a lot of coffee. "We have all been given the best education possible," said graduate Sonali Mohapatra during a shared valedictory address with fellow student Tom O'Brien.

During his keynote address, cosmologist Paul Steinhardt encouraged the students to apply their energy and tenacity to the toughest questions in the universe. "There is no question in theoretical physics that is beyond your reach," Steinhardt said. "Follow your heart, not the crowd. When you choose something to work on, it has to be something you strongly believe in your heart to be important."

SYNERGIES

Ontario Ministers Join Convergence

Ontario Finance Minister Charles Sousa and Transportation Minister Steven Del Duca joined researchers, private funders, and other guests at Convergence last June to share words of support from the province. The Ministers brought these greetings from Premier Kathleen Wynne: "Our government looks forward to continuing to work with all of you to attract the next generation of physicists, make breakthroughs, and build on our success for the future." More about Convergence on page 21 – 23.

Celebrating Innovation

Perimeter is honoured to be named a nominating partner for the new Governor General's Innovation Awards, founded by His Excellency David Johnston to recognize people and organizations making outstanding contributions to society and humanity. The inaugural awards ceremony will take place in spring 2016.

Discussing Research in Canada

Ken Knox, President of the Science, Technology and Innovation Council (STIC) for the Government of Canada, visited Perimeter to gather current insights on the Institute and discuss national directions in science with John Matlock, PI Director of External Relations and Public Affairs.

It's Elementary

Perimeter is expanding and enriching its student outreach efforts, thanks to a new partnership with Ontario's Ministry of Education (MOE). The Institute will now be able to reach younger grades and more teachers. Funding will support new programs and resources for elementary students, expand the teacher-training network, and add more math and tech content to the resources freely available to the province's teachers.

In the photo above, Education Minister Liz Sandals (centre) celebrates this extra skills-building project with (from left) Katie Williams from the MOE; Perimeter Outreach team members Kevin Reid, Jill Bryant, Damian Pope, Glenn Wagner, Ashley Kozak; and Outreach Director Greg Dick.

Exploring the Quantum Valley

Public stakeholders from all levels of government often visit Perimeter Institute and related locations to share news, discuss developments, and stay in touch. Pictured above: Perimeter Board Co-Chair Cosimo Fiorenza hosts the Federal Deputy Minister for Innovation, Science, and Economic Development, John Knubley, and the Privy Council Deputy Secretary to Cabinet, Stephen Lucas. Pictured right: Ontario Assistant Deputy Minister of Research and Innovation, Bill Mantel, joins Perimeter Chief Operating Officer Michael Duschenes and Perimeter Director Neil Turok during a visit to the Institute.

Hot Soup, Hotter Spoon?

Here's a bit of physics to contemplate as you slurp your soup. **Which is hotter:** the ceramic bowl or the metal spoon?

Since we're slurping at Perimeter, we know that if the spoon, the bowl, and the soup are all in contact with each other, they will come to thermal equilibrium. Assuming the soup has been sitting for a bit, the soup, bowl, and spoon should all be at the same temperature.

But they sure don't feel that way. The ceramic bowl will feel pleasantly warm, whereas the spoon might burn your tongue. What gives?

Short answer: what we feel is not temperature, but the rate at which heat flows into our hands. That depends on both the object's temperature and its thermal conductivity. The thermal conductivity of metal is high, while the thermal conductivity of ceramic is low.

This also works in reverse, which is why a cold piece of metal feels much colder than a cold piece of wood. (Thus, Perimeter's winter visitors should not lick flagpoles. It is not a Canadian tradition, no matter what you've heard.)

- Erin Bow

Lentil and chorizo soup

2 chorizo sausages, finely chopped
1 brown onion, finely chopped
2 garlic cloves, crushed
1 tbsp sweet paprika
1 carrot, peeled, finely chopped
1 zucchini, finely chopped
1 tomato, finely chopped
4 cups (1 litre) chicken stock
400 gram can of lentils, rinsed, drained
Crusty bread, to serve
Basil oil
1/3 cup (80 mL) olive oil
1/4 cup chopped basil

Heat a large saucepan over high heat. Add the chorizo and cook, stirring, for 2-3 minutes or until brown all over. Use a slotted spoon to transfer to a bowl.

Add the onion, garlic, and paprika; cook, stirring, for 5 minutes or until onion softens. Add the carrot, zucchini, and tomato; cook, stirring, for 2 minutes or until tender.

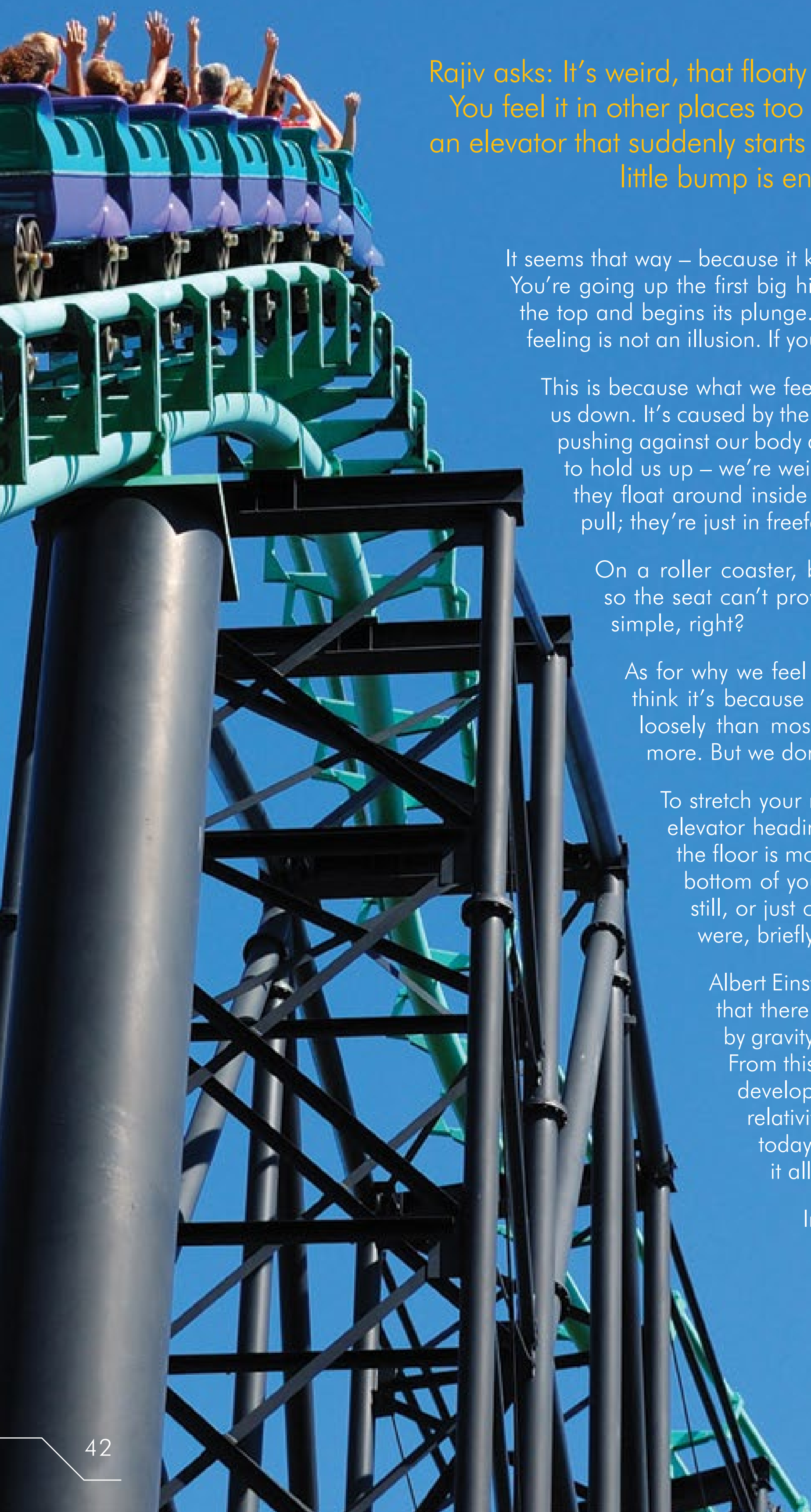
Add the chicken stock and chorizo; bring to a simmer. Cook, stirring occasionally, for 15 minutes or until vegetables are tender and soup thickens slightly. Add the lentils; stir to combine. Taste and season with salt and pepper.

Place the oil and basil in a blender and blend until smooth. Strain through a fine sieve into a jug.

Ladle soup into serving bowls. Drizzle with basil oil and serve with crusty bread.

PI KIDS ARE ASKING

Why Does Your Stomach Drop When You're on a Roller Coaster?



Rajiv asks: It's weird, that floaty feeling you get at the top of a roller coaster. You feel it in other places too – going over bumps in the road, or being in an elevator that suddenly starts heading down. Sometimes it seems like one little bump is enough to turn off something as big as gravity.

It seems that way – because it kind of is that way. Imagine being on that roller coaster. You're going up the first big hill, holding your breath, and suddenly the car tips over the top and begins its plunge. You feel yourself rising out of the seat. This weightless feeling is not an illusion. If you had a scale, you'd find that you actually weighed less.

This is because what we feel as weight is not caused by the force of gravity pulling us down. It's caused by the force of the floor (or the chair, or the roller coaster seat) pushing against our body and holding us up. When we fall – when there is nothing to hold us up – we're weightless. That's what's really happening to astronauts as they float around inside their ships. They're not out of the reach of the Earth's pull; they're just in freefall.

On a roller coaster, both you and your seat are falling at the same time, so the seat can't provide any support. No support means no weight. Pretty simple, right?

As for why we feel a roller coaster's drop specifically in our stomach, we think it's because the stomach and intestines float inside the body more loosely than most other organs, and so being weightless affects them more. But we don't really know.

To stretch your mind back in a physics direction, imagine you're on an elevator heading up, instead of down. As the elevator starts to move, the floor is moving toward you, faster and faster. It pushes against the bottom of your feet with more force than it would if it were standing still, or just climbing steadily. If you had a scale, you'd find that you were, briefly, heavier.

Albert Einstein once stretched his mind in just this way, and realized that there is no way to tell the difference between weight caused by gravity and weight caused by the floor speeding up under you. From this one idea – he called it the happiest idea of his life – he developed a brand new description of gravity called general relativity. General relativity is still the theory of gravity we use today. It is one of the great triumphs of modern physics, and it all came from Einstein imagining an elevator.

Imagine if he'd had a roller coaster!

– Erin Bow

Hey kids! Have a question?

Send it to magazine@perimeterinstitute.ca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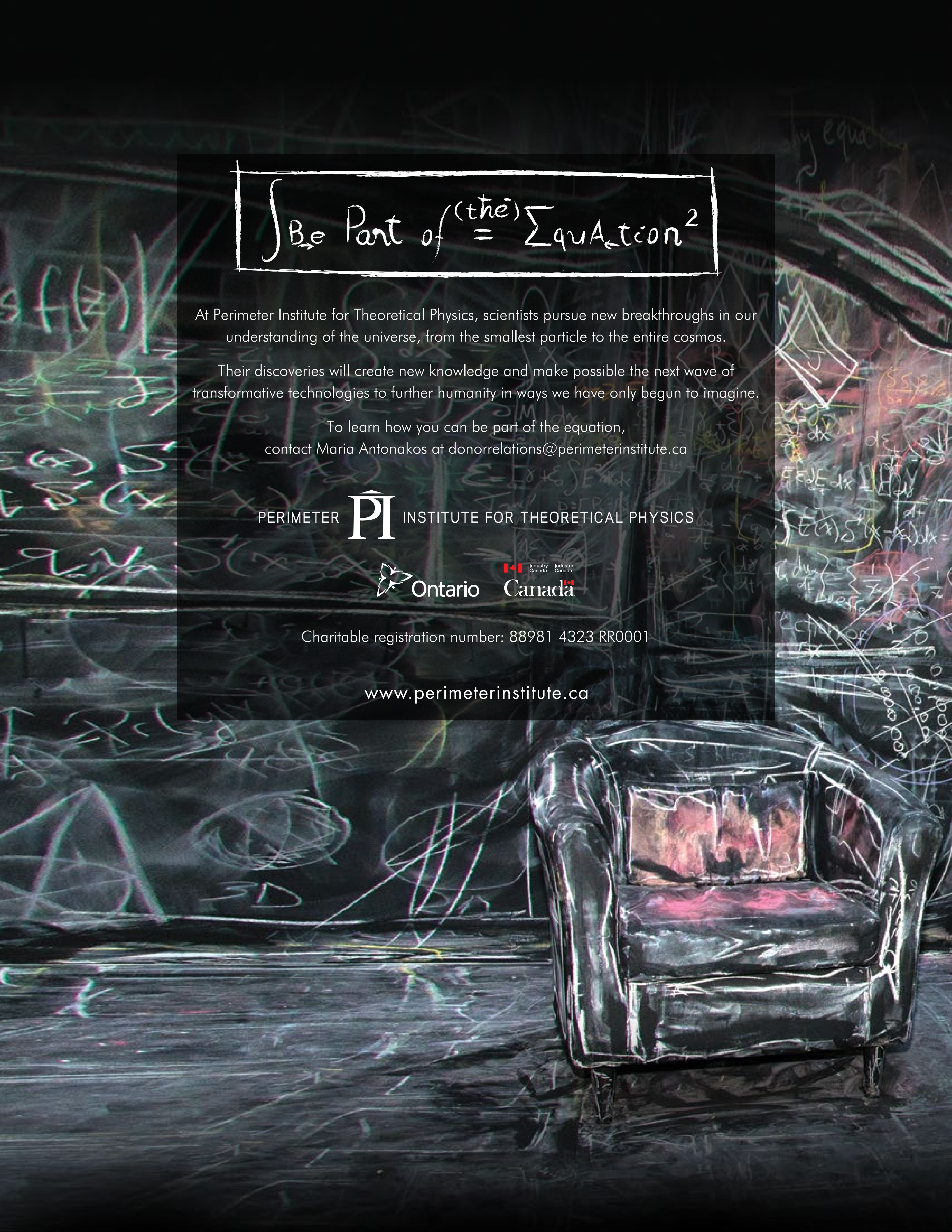
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