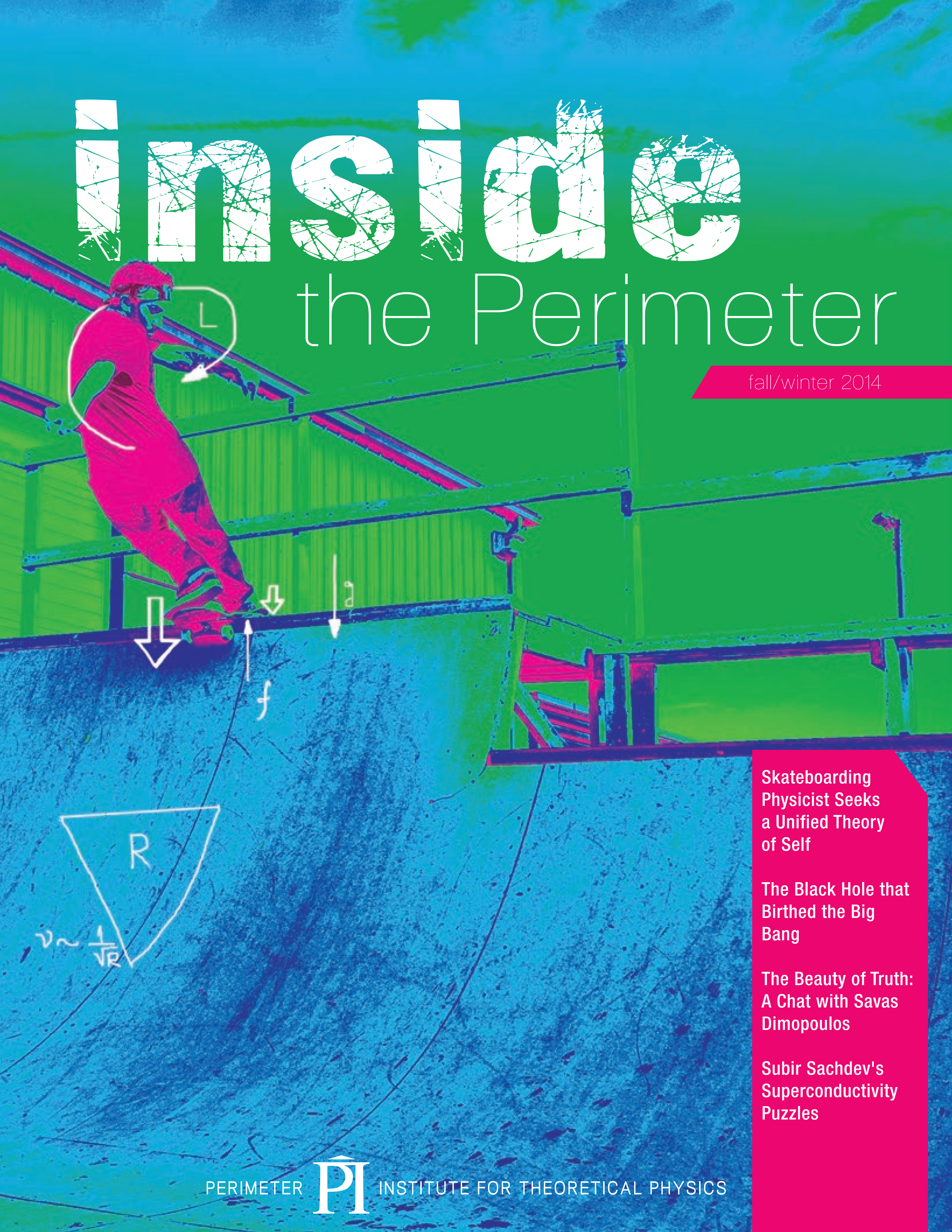
inside the Perimeter

fall/winter 2014



Skateboarding Physicist Seeks a Unified Theory of Self

The Black Hole that Birthed the Big Bang

The Beauty of Truth: A Chat with Savas Dimopoulos

Subir Sachdev's Superconductivity Puzzles

PERIMETER PI INSTITUTE FOR THEORETICAL PHYSICS

inside the Perimeter

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

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IN THIS ISSUE

Young at Heart

On the cover of this issue, on the lip of a halfpipe, teeters David "Doddy" Marsh, a young cosmologist here at Perimeter. I didn't know Doddy was a skateboarder, but it doesn't surprise me. Skateboarding is all about gravity and motion.

Navigating unfamiliar obstacles, testing out moves you've only glimpsed in your mind's eye, taking spills and hard knocks when things don't work out, picking yourself up and trying again – it's just like theoretical physics, though skateboarding scrapes are more visible. Whether at the blackboard or in the halfpipe, these are the habits that fuel breakthroughs.

While physics is probably the oldest science, it's also the youngest in outlook. Its greatest successes come from looking at the simplest of questions, with the widest eyes. How does the universe work? What's it made of? Where did it come from? Physics favours the curious, the daring, the most adventurous explorers who look beyond convention toward the impossible.

It's a great time to be doing physics. A flood of new data is pouring in from the most sophisticated experiments ever built; powerful accelerators like the Large Hadron Collider are cracking apart atomic nuclei, and telescopes of unprecedented reach are peering deeper into space and further back in time than ever before, glimpsing the universe's earliest instants.

Most excitingly, our theories are failing. The most popular paradigms – string theory, inflation, unification – have reached an impasse. They do not explain the remarkable simplicity found in the universe, nor do they resolve its great paradoxes – like the dark energy that now dominates the universe and drives its expansion, or the initial singularity from which everything emerged.

We need to break through the impasse, to find powerful new principles that will reshape our understanding of the universe around us. And they need to be simple: as Leonardo da Vinci said, "Simplicity is the ultimate sophistication."

There's a story I like about the great 19th century physicist James Clerk Maxwell, about how he and his boyhood friend Peter Tait used to go to school together, throwing ideas they called "props" (for "propositions") back and forth, the way some kids throw balls. Both were curious, geeky kids who loved nature and mathematics. I picture them walking along the road in Edinburgh, horses and dogs and street life around them, tossing props at each other – testing their limits and just having fun.

Maxwell grew into the greatest physicist of his age, unifying electricity and magnetism and discovering the nature of light. Tait likewise became a great mathematical physicist, founding the theory of knots, among other things. And throughout their lives, they continued to mail props to each other whenever they were stuck on a hard problem.

That's how it all starts – with play, daydreams, and endless puzzling.

Perimeter is a community that encourages what I like to call "critical creativity." Being imaginative is essential, but we can often learn as much or more by disproving wrong ideas, as quickly and efficiently as possible. All of this requires tenacity and considerable skill. Young people, from diverse backgrounds, are our greatest asset: an endless source of energy and enthusiasm, of challenging questions and new ideas. They have a wonderful symbiosis with senior scientists who bring experience, intuition, and (sometimes) wisdom to the mix.

Discussions in the Black Hole Bistro, over coffee or lunch or afternoon snacks, are often the place where the most interesting ideas emerge. Others' reactions and questions can provide crucial encouragement and impetus for the pursuit of new approaches.

Here's an example of a radical idea that is going around: the notion that the spacetime arena for physics may not, after all, be fundamental, but instead just an approximate aspect of some highly entangled quantum system. Many researchers here are pursuing this idea from various angles – from the big bang singularity (how did all of space emerge from a single point?), to the three families of particles (why three?), to exotic condensed matter systems (how many forms can quantum matter take?), to how gravity works on the very smallest and the very largest scales.

I try to encourage everyone at Perimeter to at least spend some of their time thinking about wild and original things. Questioning what you think you know, looking at problems upside down and backwards – that's how you make progress. It keeps us all young. But I think I'll leave the skateboarding to Doddy.

– Neil Turok

DEFINING GRAVITY, DEFYING GRAVITY

Skateboarding Physicist Seeks a Unified Theory of Self

The skateboarder's t-shirt, drenched with sweat and in constant motion, is difficult to decipher. The white lettering scrawled across its black fabric resembles a jumble of graffiti, or perhaps the logos of skateboard companies.

Only when the skateboarder comes to a rare stop – actually a wipeout (or slam, in the lingo), which leaves a thin layer of his elbow skin on the concrete – does the t-shirt become legible. Legible to the trained eye, that is.

"It's the equations of the Standard Model of particle physics," explains David "Doddy" Marsh, apparently unfazed by his quickly reddening elbow. "The shirt's from CERN."

He adds: "It's the only clean shirt I had today." Then he's off again, plunging into the concave belly of the skate park before launching skyward from one of its many ramps. He seems to hang in the air, suspended for an extra microsecond as if in defiance of the relentless gravitational force he understands so thoroughly.

In the middle distance behind him, mostly obscured by a grove of poplars, stands his workplace, the Perimeter Institute for Theoretical Physics. It's where, as a postdoctoral researcher, he spends the majority of his days trying to unravel the mystery of dark matter, the invisible glue of the universe.

Theoretical cosmology is the yin to his skateboarding yang.

For Doddy Marsh ("Only my mum calls me David"), skateboarding and theoretical physics are two halves of his whole – sometimes complementary, sometimes in opposition, both essential.

Just as quantum mechanics and general relativity provide a near-complete framework of reality while their unification remains an elusive moving target, skateboarding and physics simultaneously define and beguile Doddy.

Each of his passions is fuelled by eureka moments of tantalizing success – a new trick mastered, a new solution found to a previously vexing problem – and each offers an inexhaustible supply of new challenges.

His scuffed elbow and battered ankles are analogous to the unfinished papers and half-written computer programs in his second-storey office just down the road – all reminders that there is much more to be learned, more mastery to be achieved.

He says something rarely (if ever) heard at skateboard parks: "Today, I was trying to figure out a heuristic explanation for suppression of clustering power of axion dark matter, and how it is related to the densities of dwarf spheroidal galaxies."

Doddy careens around a curved wall of the skate park before skidding to a halt at his water bottle. Between gulps, he says something rarely (if ever) heard at skateboard parks: "Today, I was trying to figure out a heuristic explanation for suppression of clustering power of axion dark matter, and how it is related to the densities of dwarf spheroidal galaxies."

It's a mouthful even by theoretical physics standards, and it's just as tricky to explain as it is to say.

He has come to the skate park to wipe clean his mental chalkboard. Sometimes, the most vexing problems are best solved by focusing on something completely different for a while – frontside ollies and smith grinds, in this case.

"Skateboarding teaches perseverance, because it's damn hard," says Doddy. "Physics is notoriously hard too, but maybe the fact that I struggle all the time in skateboarding makes struggling with some maths problem seem less consequential."

Skateboarding makes physics easier? It's a counterintuitive notion, but Doddy is accustomed to counterintuitive notions. And for him, it's a realization borne out of many years of trial and frequently painful error.

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On Christmas morning, 2000, 13-year-old Doddy Marsh unwrapped the gift he'd been begging for: his first-ever skateboard. Like countless kids of his generation, his exposure to skateboarding had come through the PlayStation game *Tony Hawk's Pro Skater*, and he assumed he'd be replicating its death-defying virtual stunts for real in no time.

He was wrong.

He had already shown a natural aptitude for mathematics (both his parents were math teachers, which surely helped), but the ability to calculate a hypotenuse and the ability to boardslide down one,

in the form of a real-world handrail, proved quite different. What served Doddy well on both fronts was a dogged, almost obsessive, determination to leave no problem unsolved.

He immersed himself in Liverpool's legendary skateboarding scene, careening with friends around the endless obstacles provided by the city's industrial decay. He learned from veterans of the scene at Pier Head, the city's skateboarding epicentre on the banks of the River Mersey.

He built a makeshift skate park in his parents' back garden with materials "borrowed" from local construction sites, and filmed videos with his buddies performing ever-more intricate tricks, accompanied by thumping soundtracks of hip-hop and punk.

His studies, meanwhile, never flagged. On the contrary, skateboarding brought mathematics and physics into sharper resolution in his mind.

"When I was about 16, I was learning in school for the first time about simple harmonic motion and resonance and natural frequencies," he recalls. "That's when skateboarding first helped me understand a physical concept."

What he realized is that a skateboarder rolling up and down the sloped walls of a halfpipe is analogous to a pendulum, its tick-tock an expression of its period of oscillation, or natural frequency.

"There's a natural frequency determined by geometry," says Doddy. "The halfpipe, too, has a fixed geometry – the radius of curvature of its transitions – that defines a natural frequency."

Eventually, he saw that there's a well-defined (classical) physics concept for something every skateboarder knows intuitively: "Tight transitions are whippy." The natural frequency is larger when the geometric quantities are smaller – or, put another way, the smaller the pool or halfpipe, the more rollercoaster-like "whip" the skateboarder feels careening around its curvature.

Through his high school years, Doddy poured his energies equally into mathematics and skateboarding, finding ever-deeper parallels between them. Pumping his legs to gain momentum within a ramp became a "resonance response putting energy into a physical system." Jumps and tricks became experiments in inertia and friction and elasticity. Learning how to fall without breaking his wrist (again) became experiments in angular momentum and velocity.

"When I'm stuck on a problem, I often grab my board and skate. By the time I come back, the answer has made itself clear."

Of course, when he's actually in the midst of a new trick, instinct and reflex kick in, overriding the analytical parts of his brain and firing the reactive, instinctual synapses. It's that interplay of applied physics and pure physicality that makes skateboarding such a deeply satisfying activity for Doddy.

"It's meditative," he says. "When I'm stuck on a problem, I often grab my board and skate. By the time I come back, the answer has made itself clear."

***

Every skate park, like every physics problem, poses its own unique set of challenges, its own promise of a new skill or realization.

In the balmy pre-dusk of an August evening, Doddy is in the sleepy town of Wellesley, best known for its annual Apple Butter and Cheese Festival. It is 20 minutes and a world away from Perimeter Institute, where Doddy has spent the afternoon grappling with the detectability of ultra-light axionic dark matter.

The Wellesley skate park – really just a parking lot in which a local skateboarder built an impressive wooden halfpipe – is empty, save for the ketchup-soaked French fries a previous visitor spilled beside the ramp.

Warming up, Doddy glides effortlessly up and down the sides of the halfpipe, like a marble dropped in a bowl. Then, with well-timed pumps of his legs, he drives energy into the physical system, searching for the resonant peak of the ramp's curved geometry. Moments later, he's skimming the lip of the ramp.

His goal is to execute a perfect rock 'n' roll – a fundamental skateboarding trick in which the front wheels crest the lip of the ramp, the board teeter-totters for a moment at the top, and then plunges back down, preferably with rider intact. He wants to nail it, partly because there's a photographer present, but mainly because he refuses to leave a self-imposed challenge unaccomplished.

What bigger challenge, after all, could there be than the one he was tackling just an hour ago – explaining the origins, growth, and ultimate fate of the universe? Maybe his current professional fixation, determining the true nature of dark matter – the mysterious stuff that makes up a quarter of the universe's energy density – will prove as elusive as the inward heelflip, a trick Doddy has yet to successfully execute.

Then again, the rock 'n' roll atop a halfpipe seemed impossible when Doddy rode his first skateboard at age 13, but now, with a giddy yelp of satisfaction, he nails one (and is doubly pleased to learn the camera caught the moment).

He takes a breather atop the ramp, wiping his glistening brow with his left forearm, which is tattooed with a stylized version of the Anti-Hero Skateboards logo. His other arm is currently inkless, but he's considering having it adorned with the Friedmann-Robertson-Walker metric, which describes the expansion or contraction of the universe.

"That would make for good balance," he quips, only half-joking.

Skateboarding and physics are the two halves of a complex equation, and Doddy is the equals sign in the middle. There are plenty of other variables in his life, of course – music, art, Buddhism, travel – but they are always calculated against the constants.

That, as the saying goes, is just how he rolls.

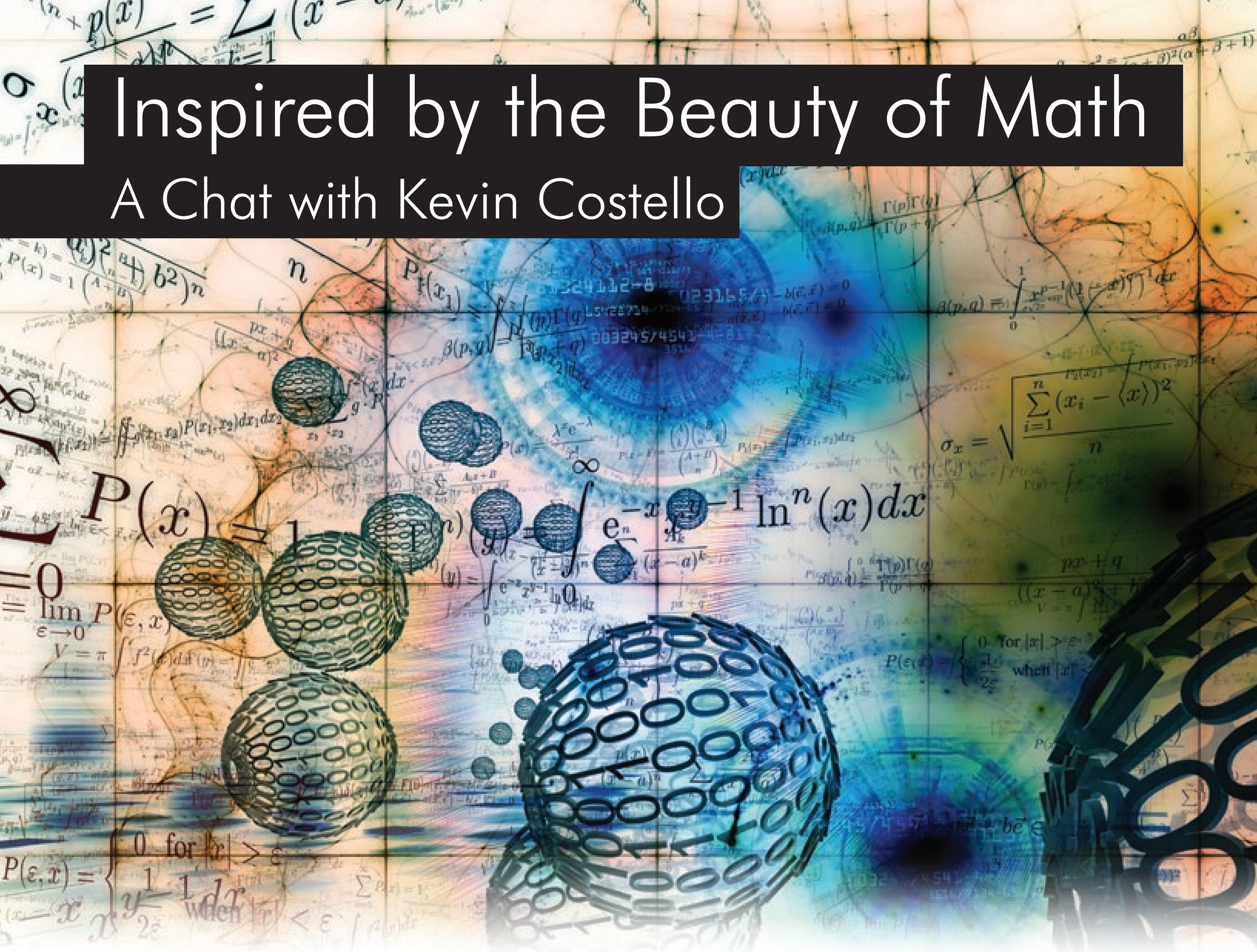
"Skateboarding and physics give me very different things in my life, but they come together in really interesting ways."

– Colin Hunter

Check out a video of Doddy Marsh on Perimeter's YouTube channel.

Inspired by the Beauty of Math

A Chat with Kevin Costello



Kevin Costello was 10 years old when he happened upon his father's collection of *Scientific American* magazines. He didn't understand much of what he found in those pages, but he was particularly captivated by the *Mathematical Games* column, a recurring feature penned for 24 years by Martin Gardner.

Costello's curiosity was piqued by columns with titles like "Fun with eggs: uncooked and mathematical" and "The imaginableness of imaginary numbers." Every time a new issue of the magazine arrived at his family home in Cork, Ireland, Costello dove into problems that required mathematical approaches he wouldn't officially learn in school until years later.

"It was hard, of course," recalls Perimeter's newest faculty member, who arrived at the Institute this summer as the Krembil Foundation William Rowan Hamilton Chair in Theoretical Physics.

"I remember one was about how to program a Mandelbrot set [a mathematical example of a complex structure arising from the application of simple rules]. And I'd try to do this on my home computer. I'm not saying I totally understood it, but it was really interesting to me."

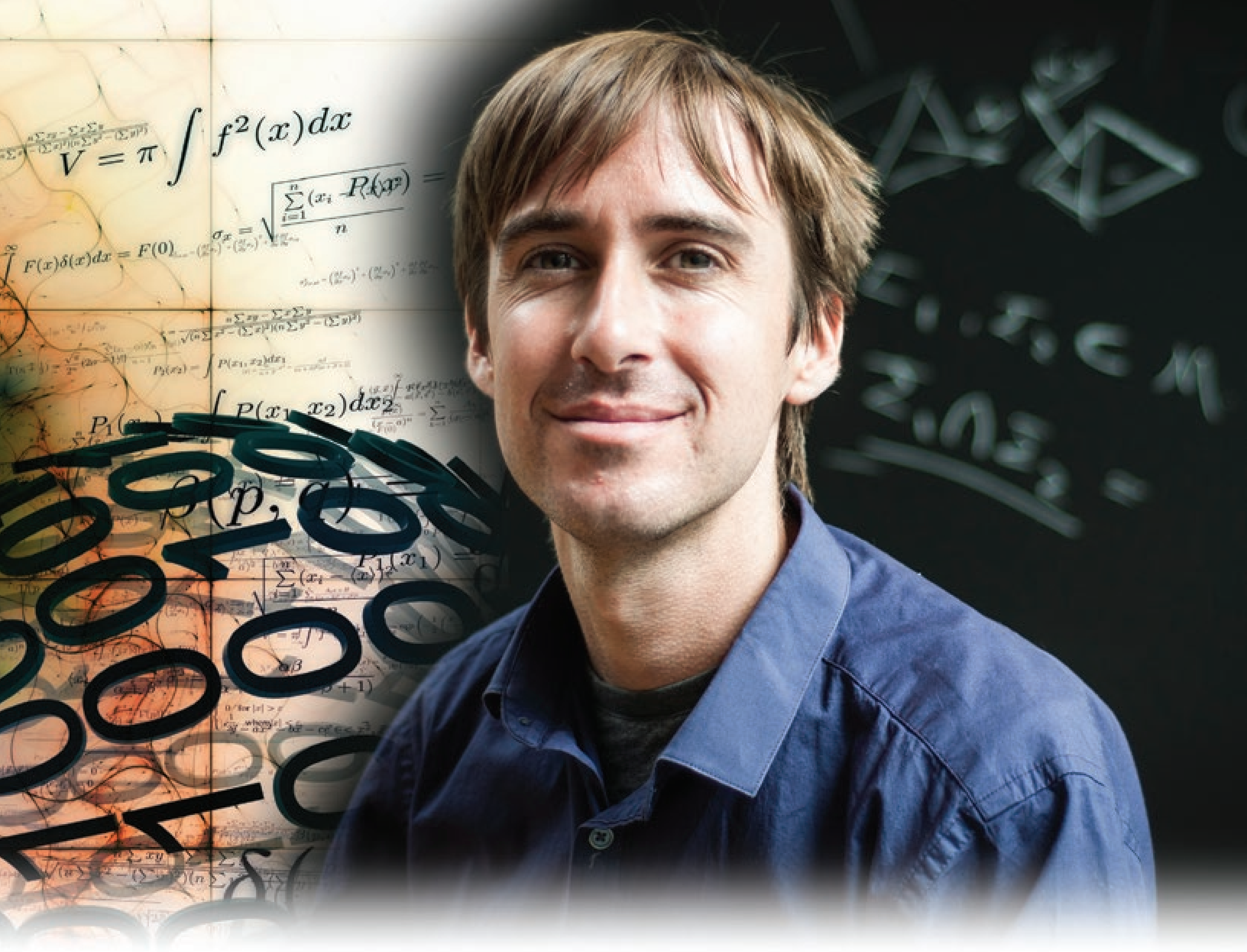
He couldn't have known at the time that he was taking the first steps down a path that would lead him to a career in mathematical physics – partly because mathematical physics was only beginning to become recognized as a distinct research area.

Historically, it would have been impossible to distinguish between theoretical physics and pure mathematics. But in the 20th century, quantum theory was developed almost simultaneously with a variety of mathematical fields, including linear algebra, the spectral theory of operators, and functional analysis.

As such, mathematical physics has become an area of increased interest at Perimeter Institute, and Costello is among the first faculty members recruited with this area of research focus.

Immersing himself in the Perimeter environment – talking and collaborating with string theorists, cosmologists, particle physicists, and others – sparks his curiosity in a way reminiscent of those *Scientific American* puzzles, he says.

"Mathematicians tend to have a different culture than physicists," he explains. "So if a mathematician and a physicist approach



the same problem, they'll always take a different point of view on it. It's always useful to get different perspectives and to look at things from different points of view."

That kind of free collaboration, he says, is what most attracted him to Perimeter and convinced him to leave a faculty position at Chicago's Northwestern University. He moved with his wife and young daughter to Waterloo because he saw Perimeter as an "ideal work environment," where he can contribute mathematical insights to a variety of questions being tackled at the Institute.

"The Krembil Foundation made this wonderful contribution to create endowed Chairs for me and Davide [Gaiotto] – it was all so attractive," he recalls. "How could I say no?"

The funding from the Krembil Foundation – a charitable organization that had largely focused its philanthropic efforts on medical research, education, and social services – allows Costello to recruit postdoctoral researchers, travel to workshops and conferences, and collaborate internationally with researchers on questions that promise to shape our understanding of the universe.

"Mathematics is a community effort," he says, "and there's a whole mathematical culture, with each of us contributing to it."

Costello's research interests are wide-ranging, but he's currently immersed in the question of supergravity, a branch of field theory that combines the principles of supersymmetry and general relativity, which he calls "a beautiful idea that is a very fun thing to try to understand."

That sense of fun in mathematical problem-solving still motivates Costello, decades after immersing himself in those *Scientific American* puzzles. It's a joy he thinks is all-too-often missed by students who struggle to learn mathematics principles by rote – who haven't yet experienced the satisfaction of reaching the solution of a difficult problem.

It's that feeling, he says, that makes him excited to arrive at work every morning.

"The beauty and joy of mathematics is what got me excited about it," he says. "Of course, that beauty is hard to describe to an outsider – someone who hasn't experienced it for themselves. It isn't a spectator sport; you really have to spend some time doing it yourself to see its beauty."

– Colin Hunter

The Black Hole that Birthed the Big Bang

In his Allegory of the Cave, the Greek philosopher Plato described prisoners who have spent their entire lives chained to the wall of a dark cavern. Behind the prisoners lies a flame, and between the flame and prisoners parade objects that cast shadows onto a wall in the prisoners' field of view. These two-dimensional shadows are the only things that the prisoners have ever seen – their only reality. Their shackles have prevented them from perceiving the true world, a realm with one additional dimension to the world that they know, a dimension rich with complexity and – unbeknownst to the prisoners – capable of explaining all that they see.

Plato was on to something.

We may all be living in a giant cosmic cave, created in the very first moments of existence. In the standard telling, the universe came into being during a big bang that started from an infinitely dense point. But according to recent calculations that we have carried out, we may be able to track the start of the universe back to an era before the big bang – an era with an additional dimension of space. This protouniverse may have left visible traces that upcoming astronomical observations could uncover.

The universe appears to us to exist in three dimensions of space and one of time – a geometry that we will refer to as the "three-dimensional universe." In our scenario, this three-dimensional universe is merely the shadow of a world with four spatial dimensions. Specifically, our entire universe came into being during a stellar implosion in this suprauniverse, an implosion that created a three-dimensional shell around a four-dimensional black hole. Our universe is that shell.

Why would we postulate something that sounds, on the face of it, so absurd? We have two reasons. First, our ideas are not idle speculation – they are firmly grounded in the mathematics that describe space and time.

Over the past couple of decades, physicists have developed a rich theory of holography, a set of mathematical tools that allows them to translate descriptions of events in one dimension to the physics of a different dimension. For example, researchers can solve relatively straightforward equations of fluid dynamics in two dimensions and use those solutions to understand what is going on in a much more complicated system – for example, the dynamics of a three-dimensional black hole. Mathematically, the two descriptions are interchangeable – the fluid serves as a perfect analogue for the extraordinary black hole.

The success of holography has convinced many scientists that more is at work here than a simple mathematical transformation. Perhaps the boundaries between dimensions are less stable than we thought. Perhaps the rules of the cosmos are written in another set of dimensions and translated into the three we perceive. Perhaps, like Plato's prisoners, our personal circumstances have tricked us into believing the world is three-dimensional when in fact a deeper understanding of what we perceive will come only when we look for explanations in the fourth dimension.

The second reason that our four-dimensional universe is worth thinking about is because a close study of this universe could help us understand deep questions about the origin and nature of the cosmos. Consider, for example, the big bang, the primordial flash that brought our universe into existence. Modern cosmology holds that the big bang was immediately followed by "inflation" – a period of rapid expansion of space in which the early universe increased its volume by a factor of 10^{78} (or more). Yet this expansion provides no insight into what caused the big bang. Our four-dimensional universe, in contrast, gives us an answer to the ultimate mystery: Where did the universe come from?

Our investigations into the four-dimensional universe came about because of the problems that we have had contemplating the three-dimensional one. Modern cosmology has been fantastically successful, but its successes belie deep and complex mysteries that may lend themselves to a holographic explanation.

– Niayesh Afshordi, Robert B. Mann, and Razieh Pourhasan

Excerpted with permission from *Scientific American*, August 2014

Read the whole story in *Scientific American*.

Watch a video about this research.

Is the Universe a Bubble?

Cosmology has traditionally sought to explain the origins, growth, and fate of our universe. But what if "our universe" is not all that's out there?

What if our universe is just one bubble in a frothing sea of universes, as suggested by the so-called multiverse hypothesis, which has been gaining ground in the last decade or so?

The hypothesis emerged as a consequence of what we think we know about cosmic inflation, a proposed moment of accelerated cosmic expansion a fraction of a second after the big bang.

The idea that our universe is one of many universes – perhaps an infinite number of them – has fuelled much debate within the cosmological community. Even if other universes exist outside our own, critics of the theory argue, they are by definition beyond our observation and scrutiny, and therefore a question for the consideration of philosophers, not scientists.

But while the multiverse may forever lie beyond our direct observation, perhaps it is possible to indirectly observe its effects on our own, akin to how we see wind in the swaying of trees.

Perimeter researchers Matthew Johnson and Luis Lehner have proposed a scenario in which another "bubble" universe bumps into our own, leaving behind a trace of this cosmic collision. Using computer simulations, the researchers demonstrated how such a collision could leave a tell-tale "bruise" on the cosmic microwave background (or CMB, the earliest light in our universe).

The researchers started by simulating a simple multiverse with just two bubbles in it. They had the bubbles collide in various ways, and then added an "observer" to various locations within the simulation to sort out what the observer would see. What they concluded is that, if our own universe had bumped against a neighbouring universe, an observer (with sophisticated telescopes) might see a "disc" imprinted on the CMB.

This research marks the first time, as the team writes in a recent paper, that anyone has devised a direct set of quantitative predictions for the observable signatures of colliding bubble universes. That is, they have transitioned the multiverse hypothesis out of the realm of metaphysics and into the realm of testable physics.

"I think a nice part of this work, even if we don't find any evidence for other universes, is that it shows there are indeed ideas about the multiverse that can be tested with experiment," says Johnson.

"There are now models that can be falsified, which is the mark of a scientific theory. That's an important step in the direction of putting this idea of the multiverse on scientific footing."

– Colin Hunter

Probing Nature's Building Blocks

Raffi Budakian has invented a new way to examine microscopic phenomena.

A new associate faculty member at Perimeter and a professor at the University of Waterloo, Budakian designs and builds ultra-sensitive detection instruments that allow us to look at nature in fundamentally new ways.

"Any time you have a new tool to study a system, you end up learning new things about that system," he says. "Historically, this is how most scientific discoveries are generated, and it's a process that continues today."

To see something new, Budakian has had to get small – really small. The instrument he uses is as long as a human hair is wide and has the circumference of a virus.

Magnetic resonance force microscopy (MRFM) combines two powerful tools for investigating nature: magnetic resonance (the technique behind magnetic resonance imaging, or MRI) and force microscopy (examining tiny things by measuring the forces that act on them).

An MRI machine reveals tissues and structures inside the body by measuring the fundamental unit of magnetism, called spin, in a very clever way.

Your body, mostly water, is full of H_20 molecules. Hydrogen atoms have one of the strongest nuclear magnetic moments and a specific spin frequency, so when an MRI machine imposes a magnetic field of known strength on the entire body, it can spot the spins of just the protons in those water molecules. Get enough protons together and you can generate an accurate image of what's happening inside without ever needing a scalpel.

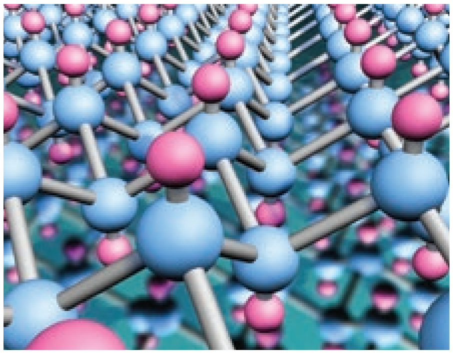
"MRI is great for something as big as a human body, but only works if you have lots of protons around to construct a signal," says Budakian.

"The sensitivity of MRFM is billions of times better than an MRI machine. With MRFM, you can image things like single molecules, virus particles, and proteins. You can make slice-by-slice images of very tiny things without destroying them, and you can get chemical information by learning what the atoms are inside and how they're arranged."

Using the new tool of MRFM, Budakian is investigating fundamental questions about nature.

"This tool has many implications for social and scientific problems. In structural biology, it will let scientists examine a single virus and discover exactly how it's made, including chemical information, which will be transformative for the discipline," explains Budakian.

"In condensed matter, where we study the physics of materials and correlated systems, MRFM helps us understand many-body effects – phenomena that come about when many particles interact to give rise to a collective excitation or state-of-matter. Usually, you can only measure what's called the 'bulk' – all the particles together.



MRFM lets us make local, incredibly precise measurements at the nanometer scale. This will help us learn more about states of matter like superconductivity, where the interesting stuff seems to be happening at the surface."

For something with a name like magnetic resonance force microscopy, "the instrument itself is surprisingly simple," says Budakian, bringing up a 3D image on his laptop.

"We just need to detect forces: if we can measure the magnetic field of something, we can know its spin. So, we take a sample, put it on a tiny cantilever, and pass it over what we need to measure using magnetic resonance to encode only the spins we want. The movement of the cantilever gives us the measurement we need. As you can imagine, the difficult part is nanoengineering an instrument small enough, and precise enough, to make these measurements."

There's only one way to build a cantilever that small: by not *building* it at all.

"The most sensitive instruments we use are actually grown," he explains. "They start with a catalyst particle: a very tiny gold particle on a surface of silicon. We place the catalyst in a furnace with silane gas, which contains silicon that bonds to the gold at high temperatures. Eventually, you get a tiny rod of silicon that has grown preferentially on the gold – and voilà."

The final cantilever is about 50 nanometers across and 20 microns long.

"That's our mechanical object," says Budakian. "We attach a molecule of what we want to interact with on the very tip of this rod and bring it near the object that generates the magnetic field gradient and resonance, all at a very low temperature. From that, we get our measurements and then our image."

It's a feat that demonstrates what happens when discoveries of theoretical condensed matter physics are put to the test in the lab. That kind of blackboard-to-laboratory collaboration is exactly what drew Budakian to Perimeter and Waterloo.

"The people I interact with are varied; I deal with scientists asking fundamental questions, and ask them myself, but I also work with engineers who know how to build things," he says.

"Having Perimeter and the Institute for Quantum Computing (IQC) right next to each other was absolutely a draw for me to come here because our technique is fundamentally a quantum technique. Having people with technical expertise at IQC is exciting – I can dream about experiments I couldn't before.

"At Perimeter, where the focus is theoretical, I get access to lots of different ideas. Just yesterday, I was interacting with a group of cosmologists who are dealing with problems whose effects are felt by spin. Perimeter allows for these unexpected avenues, broader applications for our techniques and tools. These aren't research programs now, just fun and stimulating things to think about, but that's part of the process."

– Phil Froklage

The Beauty of Truth

A Chat with Savas Dimopoulos

To Savas Dimopoulos, science is an intimate conversation with nature. Dimopoulos, a Distinguished Visiting Research Chair at Perimeter, has spent his career conversing with nature through his work at CERN's Large Hadron Collider and his long tenure as a professor of physics at Stanford University. He recently made his big-screen debut as a featured scientist in *Particle Fever*, a documentary about the long quest for the Higgs boson.

Inside the Perimeter sat down with Dimopoulos to discuss the beauty of science, the questions that drive him, and his newfound fame as a movie star.

Inside the Perimeter: Your work is known for building bridges between theory and experiment. Why is it important to have a foothold in both areas?

SD: Both theory and experiment are exceedingly important, and one without the other cannot continue. If all we do is theories on blackboards, we can invent mathematics but we're not necessarily exploring nature. With just experiment and no theory, you get measurements but you don't know how to interpret them – they are without order. Science is not just measurement; you want to have understanding. Understanding means, from very few principles, being able to explain and predict many things – from the behaviour of particles to how galaxies work. Nature turns out to be exceedingly simple in principles and exceedingly complex in phenomena. You can write the laws of nature on a piece of paper and they explain everything we've seen so far.

Inside: How does it feel to have a theory you've worked on be confirmed by experiment?

SD: I've only had one such experience in my life and it was one of the greatest feelings. You know what it feels like? It feels like a gift we didn't deserve. When we do science on a day-to-day basis, it's sort of like a puzzle – this very intricate game with strict rules. It's like nature is a giant puzzle and mathematics is the language of nature. And then when a mathematical theory is verified by experiment – you feel an awe, an amazement, a wow.

Inside: You've investigated so many fundamental questions in your research. What's currently keeping you up at night?

SD: I think a lot about the very interesting connection between the cosmos and elementary particles. When I was a student, I started to think about this connection. It was very non-traditional then, but now elementary particles and cosmology are becoming very closely connected, which is very exciting. It keeps me up at night, but not in a bad way. I tend to wake up in the middle of the night and my mind is full of thoughts. I don't know what happens when I'm asleep, but ideas and concepts crystalize in my mind somehow. It's not like there's no knowledge before sleep, but there's no order to the knowledge. As I sleep, things get put in order. So I wake up very often with very clear thoughts – the same facts, but rearranged in a more meaningful away.

Inside: Are you dreaming about particle collisions at the Large Hadron Collider?

SD: Yes, sometimes. The Large Hadron Collider is going to turn back on in January 2015, and it's going to be double the energy as before. It has a good chance of discovering things I have dreamed about – something called supersymmetry and theories with extra dimensions – and there is a lot of excitement about what it is going to discover. But much of my thinking in the interim has to do with what are called small-scale experiments – clever experiments that, unlike accelerators, don't involve thousands of people working for decades with billions of dollars. They are small-scale laboratory experiments that can nevertheless produce very fundamental discoveries. They may discover the dark matter of the universe, or new dimensions of space. The payoff can be large with a relatively small investment of resources and time.

Inside: What attracted you to science?

SD: What took me in the direction of mathematics and physics is the certainty of the truth of the statements made in them. It goes back to my childhood. I was born in Constantinople to Greek parents, and I witnessed a lot of ethnic tensions, and eventually we were expelled from Constantinople and went to Athens. There was a lot of political turmoil, people with different points of view on the left and on the right. You'd hear people on the left speaking and you'd think, "That sounds reasonable." And you'd hear people on the right and think, "That sounds reasonable." I wanted to seek an absolute truth – a truth that didn't depend on the eloquence of the speaker.

Inside: Is that kind of truth attainable?

SD: Plato believed that there are the objects we work with on Earth and these objects have idealized counterparts in a world of ideas. Think of a sphere, a ball. In real life, it's never perfect – there are always bumps and imperfections. Plato believed that there is a place of true spheres. This Platonic world of ideals is what we call mathematics. Mathematical entities and truths live in our minds; they are not necessarily realized in nature. This made me feel uncomfortable as a child: How can we be sure that a mathematical truth or "theorem" is actually correct? How can we be sure that all the people that checked it did not make an error in proving it? I felt that having a mathematical truth also be realized in nature and be checked by experiment, as it is in physics, gives it an additional layer of certainty, a better chance that it is an absolute truth. It is for this reason that I chose to study physics instead of mathematics. It is a window to the truth that I could not have gotten from just literature or art, which I also love.

Inside: Do art and literature complement your scientific work?

SD: Humans are advanced mammals that love patterns – we find them very satisfying. We are pattern junkies. Science is the search for patterns in the universe. Art is like playing games with patterns – especially music, which is a very abstract form of art. When I go home after a hard day of research, I listen to music. Those patterns, because I don't have to actively scrutinize them, I find very relaxing. I think art is very important, just as science is important. It's amazing that the least important things for our survival are the very things that make us human.

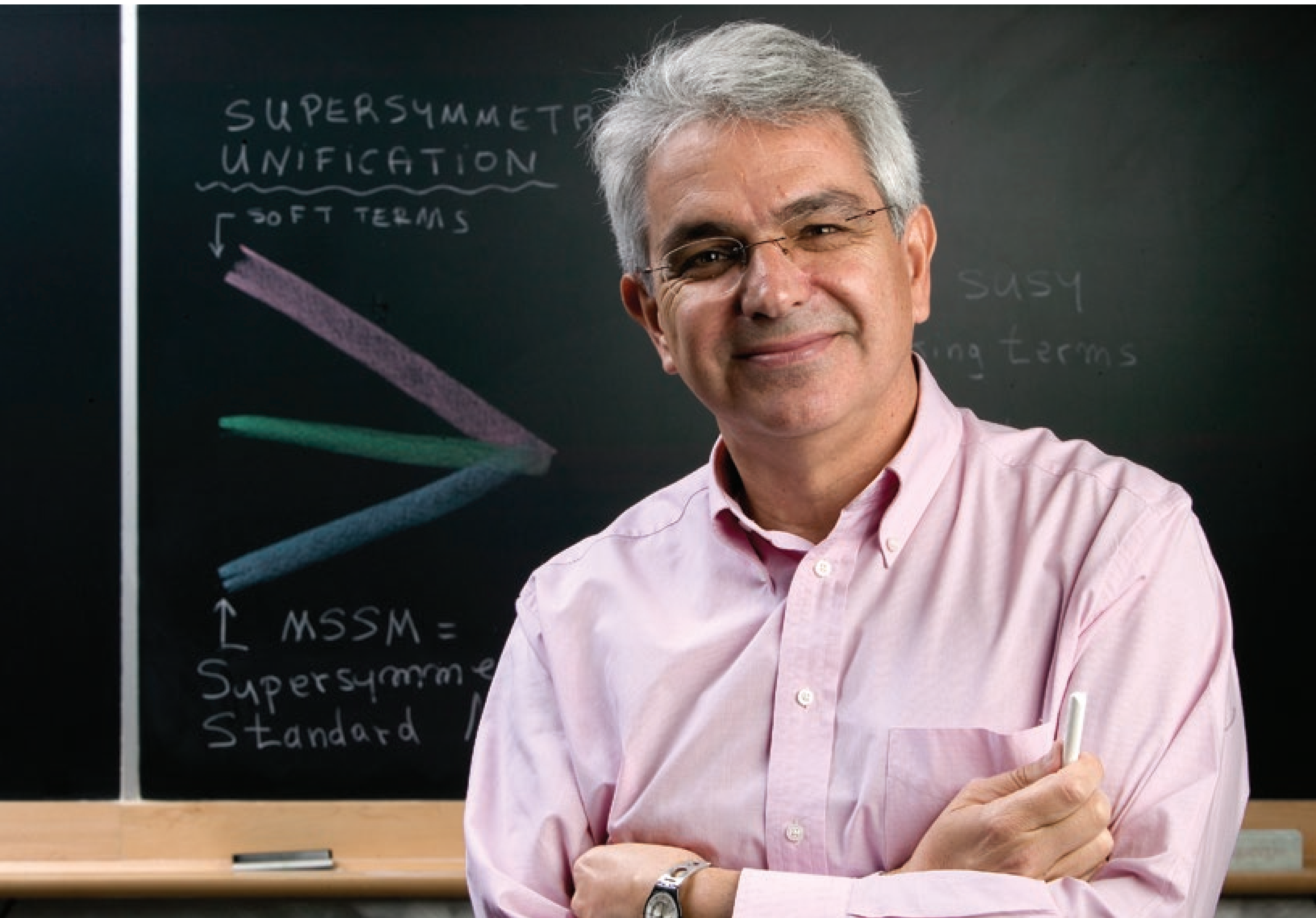
Inside: That's an idea you expressed in *Particle Fever.* Why did you want to be in the documentary?

SD: That movie was filmed over six years, and there were long stretches when I was followed every day, from morning to evening. So during the process, as you can imagine, it interfered with my life, but I felt like it was important. I knew the people who were making the film had the idea of showing the world how people seek the absolute truth through science. So while the movie was being made, I had to keep reminding myself that it's for an important purpose. And when I went to watch it for the first time at a film festival in Sheffield, the theatre was packed. I had no idea what to expect. I was so tense, and the producer sitting next to me was even more tense, shaking in his chair. But after an hour and a half, I realized that they did a really good job. For a documentary, it has done very well. For a science documentary, it did spectacularly well. So I feel it did what I hoped it would do. I hope it will have the same effect on young people that some of my science books had on me when I was a child.

Inside: What do you foresee for the coming generations of scientists?

SD: The most important discoveries are the ones that have not been predicted. Even my limited career has been full of surprises. I've been surprised by reality, and reality is far more imaginative than it has a right to be. Discoveries come out of the blue and change everything. I believe in excellence – excellent research, excellent people with an extremely broad range of interests, both theoretical and experimental. Think big – big and broad. That's where an institution like Perimeter enters. It cultivates the interactions that happen among amazing people. Get the best people, get them to mix, and great things will happen. For me, that's a self-evident truth.

– Interview by Colin Hunter



RENORMALIZATION GROUP APPROACHES TO QUANTUM GRAVITY

April 22-25, 2014

In physics, scale is (almost) everything. Our description of physical systems depends strongly on the scale at which we look at them. For instance, if you wanted to know how your tea would spread across the table if you spilled it, you would describe the puddle with hydrodynamics, and completely ignore the fact that the tea actually consists of single molecules and has a complex microscopic structure. But if you wanted to know details about how a very small drop behaved, you would use a description that takes the microscopic structure into account.

Physicists have a powerful suite of mathematical tools for "flowing" a theory at one scale into a theory at a different scale. These tools are collectively known as the renormalization group, or RG.

Renormalization group tools allow physicists to take what they know about tea molecules and move seamlessly to a description of a spreading puddle. Like the zoom lens on a camera, RG changes the distance scale. It's perhaps simplistic, but nonetheless true, that distance scales are exactly what separates quantum theory from gravitational theory – one is the physics of the small and one is the physics of the large. Could the renormalization group be the tool that finally unites them?

The "Renormalization Group Approaches to Quantum Gravity" conference was a landmark of sorts: the first gathering of researchers working on different models of quantum gravity who use the renormalization group in different forms. About 50 researchers gathered for four days to discuss conceptual as well as more technical questions, and establish a new dialogue between different quantum gravity approaches.

Support for this workshop was provided
by the John Templeton Foundation.

Action at a Distance

June 22, 2014

Albert Einstein described quantum entanglement, in which two particles share an intrinsic connection even if separated by vast expanses, as "spooky action at a distance."

He would likely be amazed (if not a bit spooked) by how, thanks to digital communications, people can now be instantaneously connected, even if separated by vast distances.

Whereas Einstein had to travel by ship and train to scientific conferences, the participants in Perimeter Institute's inaugural "Action at a Distance" conference were able to share and debate ideas, regardless of their individual locations.

The one-day conference in June brought together – virtually, via videoconference – alumni of the Perimeter Scholars International (PSI) graduate program, who have since fanned out around the world to pursue careers in areas spanning academia, industry, and actual rocket science.

PSI alumna Brigette Riley, for instance, delivered a presentation about her career as an engineer at SpaceX, the California-based private space travel company with its sights set on Mars. Whereas Riley delivered her talk in Perimeter's Sky Room, other participants asked questions and made their own presentations via teleconference.

Other presenters described how their PSI experience prepared them for PhD studies, postdoctoral work, or high-tech careers.

Held the day after the celebration ceremony for the graduating PSI class of 2013/14, "Action at a Distance" built upon the close, collaborative relationships that students form during the intense, year-long graduate program.

"The students from every PSI class form very strong bonds and friendships," said Tibra Ali, a PSI Fellow who has worked closely with students in the program since its inception. "It just makes sense scientifically and also in terms of career networking for PI alumni to have some sort of network. It was pretty awesome to have people joining in, both from over the net and locally."

Low Energy Challenges for High-Energy Physicists

May 26-30, 2014

High-energy physics and condensed matter physics might seem worlds apart. One's experiments are usually big, the other's small. One's big-bang hot; the other's often outer-space cold. One's often interested in just a handful of particles at a time; the other deals with systems that can contain trillions upon trillions of particles.

But high-energy physics and condensed matter physics both use the language of quantum field theory, and the two fields share a long history of cross-pollination. Dirac's ideas about the positron made sense of semi-conductors. Condensed matter's theories about spontaneous symmetry-breaking pushed particle physics forward. It's no exaggeration to say that the cross-talk between condensed matter and high-energy has been instrumental in shaping our understanding of quantum field theory – and the universe – as a whole.

Scientists with a high-energy background have often been attracted to condensed matter systems because their phenomenology is rich. Many have recently expanded their horizons in this direction, but often at the cost of working in relative isolation. This summer, Perimeter hosted a conference to break that isolation and reinvigorate the fruitful collaboration between high-energy and condensed matter physicists. "Low Energy Challenges for High-Energy Physicists" brought together about 40 high-energy physicists and leading condensed matter theorists.

Their goal was to unite, focus, and inspire a new community, bent on tackling some of the most interesting problems in modern physics.

Discussions and talks focused on the most pressing theoretical challenges and experimental puzzles in condensed matter physics, and how they might be tackled with modern high-energy physics techniques. The talks given by the experimentalists were particularly useful to provide the theorists with an overview of the state of the art in numerical simulations of quantum turbulence, experimental hydrodynamics, and visualizations of quantum matter.

This conference provided a vibrant and collaborative forum, and may well become a recurring event.

Other recent conferences

SUPERSYMMETRIC QUANTUM FIELD THEORIES IN FIVE AND SIX DIMENSIONS

April 24-26, 2014

Scientific Area: Quantum Fields and Strings

QUANTUM MANY-BODY DYNAMICS

May 12-16, 2014

Scientific Areas: Condensed Matter Physics, High Energy Physics, Quantum Information

NEW IDEAS IN LOW-ENERGY TESTS OF FUNDAMENTAL PHYSICS

June 16-19, 2014

Scientific Area: Condensed Matter Physics

INTERNATIONAL WORKSHOP ON QUANTUM LDPC CODES

July 14-16, 2014

Scientific Areas: Quantum Information, Quantum Foundations

Check perimeterinstitute.ca for conference updates

Upcoming Conferences

SUPERLUMINALITY IN EFFECTIVE FIELD THEORIES FOR COSMOLOGY

April 9-11, 2015

Scientific Area: Cosmology

(MOCK) MODULARITY, MOONSHINE AND STRING THEORY

April 13-17, 2015

Scientific Area: Quantum Fields and Strings

Back to the Classroom

It's the coffee break on the third day of the boot-camp for high school physics teachers that's known as EinsteinPlus.

Twenty-odd teachers have gathered at the tables in the peacock-blue workroom usually used by Perimeter's masters' students. Some are deep in conversations, some are scribbling in notebooks, some are staring into space, and a handful are playing with the toy plastic poppers that have been set out for the next exercise.

They're about to start a session called Black Holes Part One. It's the fourth session of the day – they've already been through Cosmology Parts One, Two, and Three.

"I'm starting to understand what some of my kids go through," says Michael Strange, who teaches physics and coaches soccer at Kennedale High School, south of Arlington, Texas. "I think my brain might be full."

Yet Strange and all of the other teachers have happily exchanged a week of their summer vacation to be here.

"Could we put the poppers away, please?" The facilitator, Karen Jo Matsler, has a no-nonsense manner that comes from 20 years teaching high school physics. She puts three questions up on the board:

How do we know there are black holes and how do we find them?
Why is time dilated near a black hole?
How does light behave near a black hole?

She assigns one question to each table and gives the teachers two minutes to discuss it – before cutting them off. "I want you to write down something about your question," she says. "It doesn't have to be right. But I want you to commit to something."

The teachers, it seems, have become the students.

There's a quick change of gear as a discussion breaks out on how to use warm-up exercises like this to engage students without intimidating them. But then it's right back into the student role – out come the poppers.

Poppers are like hollow rubber balls that have been cut in half. When they're turned inside out, they become unstable and leap off the table with surprising force. The teacher participants are asked to predict how fast the poppers leap, and then each table tries to design an experiment to measure the popper's launch speed.

Half-spheres of neon-coloured plastic go flying everywhere. The room fills with chatter and the click of calculators. One group is doing a video analysis with a smartphone. Each group has someone holding up a yardstick. The group at the front of the room is scribbling equations on their whiteboard.

Just five minutes later, they're comparing results. Equations fly fast.

"Teacher hat," says the facilitator, and outlines the stages of learning they've just passed through: engagement and exploration. The PowerPoint shows one way the problem can be solved. The class moves rapidly through another set of exercises, connecting launch velocity to escape velocity – the speed it takes to "break free" from the gravitational attraction of a massive body (such as the Earth). It's just 20 minutes into the workshop, but the teacher-students have already reached outer space.

Perimeter's Senior Manager of Scientific Outreach, Damian Pope, takes over the facilitating and asks a surprisingly simple question: What would happen if the escape velocity was greater than c, the speed of light?

Bang: we're in a black hole.

The thesis of EinsteinPlus is that modern physics is closer than you think. It can – and should – be brought into the high school classroom, because it's where the really cool ideas are – the mind-bending ones that can really engage kids' imaginations and ingenuity. And for almost a decade, with hundreds of teachers, EinsteinPlus has done just that.

Stacey Harvey, who teaches math and physics at a small school in Saskatoon, Saskatchewan, agrees: "Kids have a lot of questions about modern physics. They hear about it online. They're talking about it with their friends. Some of them are reading about it. Even now, in my classes, kids come in talking about quantum stuff and asking questions. We look things up together. But it happens mostly at breaks and at lunch."

Things are changing, however, she adds: "We just got a new curriculum in Saskatchewan. There's going to be some quantum mechanics and other modern physics in the curriculum. I'm very excited and I think the kids will be too. This is what is happening in science right now. This is where the excitement is."

Michael Strange agrees: "My kids are interested in black holes, in where the universe came from, in quantum mechanics. They like the big questions."

EinsteinPlus gives teachers the tools to explore today's new material in the classroom – literally the tools, in Harvey's case. "I didn't get my physics equipment ordered before I left, and it's a good thing," she says. "Every night, I've been e-mailing the secretary ordering things. Polarization glasses. Stretchy fabric. Those poppers went on the list today. Next year's class is going to have so much fun."

"Fun" is the key word. What the teachers are most interested in recapturing is the feel of the program – the dive-right-in, get-your-hands-dirty appeal of science as scientists do it.

"I like the emphasis on science as a model," says Harvey. "There was a Newtonian model of gravity and now there's the relativity model of gravity. These are the features of those models. This is how they came about. These are their limitations. It is better for students to understand models than it is for them to memorize facts."

"My kids aren't ready to tackle the mathematics of modern particle physics," says Strange. "I wouldn't even try to teach them that. I'd just lose them. But they can learn the feel of modern particle physics – they can get a taste of how it was discovered and how it fits together.

"I know they can learn it. I'm sure they can, because I just learned it yesterday. It was an amazing feeling of discovery. I can't wait to share it."

– Erin Bow

EinsteinPlus helps high school physics teachers bring black holes and quantum mechanics into their classrooms. This year's camp ran from Sunday, July 6 to Saturday, July 12.

Interested in EinsteinPlus? The program runs every summer. Applications for the 2015 edition of EinsteinPlus will open December 5, 2014.

Perimeter also offers lots of other supports and ideas for teachers and students.

Check out perimeterinstitute.ca/outreach to learn more.

Finding the Door

"No, look," Felippe Marega says, picking up a piece of purple chalk. "We can start here."

Felippe is 16 years old. He and four other high school students are attempting to answer a simple yet impossibly abstruse question: How many photons are coming out of the light bulb overhead?

It's an unusual hurdle for a teenager to clear, but these kids have brought it on themselves. First, they enrolled in the International Summer School for Young Physicists (ISSYP), Perimeter's two-week summer camp for high school students. Then, they went through a week of classes on quantum mechanics and relativity. They've been to SNOLAB, the huge neutrino observatory in Sudbury. They've observed gravity and falling things up close and personal at Niagara Falls. They've stayed up late and got up early and made trips to the coffee machine, where they bump elbows with everyone from masters' students to the giants of modern cosmology.

But now, on day nine of ISSYP, it's finally time to start learning not just about physics, but how to *be* physicists.

The trick – the hard and basic and perhaps unteachable trick – is to find a door into a problem. They need a place to start.

Back to the light bulbs. Felippe, Janay, Martin, Winnie, and Anya are gathered around the board – each holding chalk. They are, at least for the moment, baffled.

Their tutor, Perimeter postdoc Astrid Eichhorn, has been walking them through a big question for the last hour: What is the world made of? They've gone back to basics, first learning how we know things are made out of atoms, then learning how we know that atoms themselves are made of smaller things and are, in fact, mostly empty space.

"This chair, for instance," Astrid says, "is mostly not here."

Less than an hour in, the students have reached the world of elementary particle physics, of electrons, quarks, photons, and their exotic cousins – the world of particle physics as it's done today. They've talked about the particles of light, the photons. But Astrid is about to stump them.

"Why," she says, "if light is a photon, do I not see photons? Little flashes – that's what you'd expect, from particles of light."

"Because there are so many of them," guesses Janay.

Martin nods: "It's like a stream of water – you don't see molecules; you see a stream."

"How many photons are there?" Astrid asks, putting on a mock-skeptical face that would do credit to Socrates. "I don't think I believe you. Can you convince me? Can you calculate how many?"

So the five kids gather at the blackboard, each with chalk in hand, but not a mark on the board. There's murmuring. No one knows where to start. It's not as if light bulbs are rated by the number of photons they give off – they're labeled in watts.

They toss each other the facts they know about photons. They are particles of light. They are bosons. They are excitations in the electromagnetic field. They come in different wavelengths.

"Particles have wavelengths?" Astrid asks. "How does that work? Isn't it waves that have wavelengths? What do particles have?"

And then, suddenly, the door to the problem opens. Anya remembers something she learned in the quantum mechanics lectures last week: Einstein's great discovery that the energy of a photon is equal to its wavelength times Planck's constant. Martin knows that the watts of the light bulb are a measure of power – that is, of energy per second. Both equations go on the board. Now they know how much energy each photon has, and they know how much energy the light is giving off. It's a matter of math.

Together, the students crunch through the problem. Astrid coaxes them to do math as physicists do it in these back-of-the-envelope calculations. "Five divided by three is approximately one," she says.

They balk.

"The hypothesis is that there are a lot of photons. Just get it to a few orders of magnitude," she explains. "Is it a hundred? A million? A trillion trillion?"

So they set five divided by three equal to one. Martin drags out Planck's constant from memory: 6.626×10^{-34}. "Six-point-six is approximately equal to 10," says Felippe.

There's more math, cancelling of exponents, checking of units. "The units are the most important thing," says Astrid. "It's far more important to know that the units of Planck's constant are joule-seconds than it is to know its value to four decimal points."

The end result of this calculation: there are 10^{20} photons given off by a 100-watt light bulb. Seeing one of them in a flash would be like spotting each drop of Niagara Falls.

The students sit down, exhilarated. By the end of the week, they will do incredible things at this blackboard. They will design an experiment that uses a cloud chamber to spot antimatter. "Yes, that's how they did it," says Astrid. "You're just a little late – if you'd have figured that out in the 1930s, you could have had Carl Anderson's Nobel Prize."

They will learn to predict the decays of exotic particles, including the famous Higgs boson. They will even dip a toe into the big mysteries of modern physics, where there are no answers – what is dark matter? Is supersymmetry real?

But the moment of the light bulb may remain as the brightest point of the whole ISSYP experience. For physicists – even very young ones – there is no greater feeling than the moment the door opens.

– Erin Bow

ISSYP was generously supported in 2013/14 by RBC Foundation.

As part of the ISSYP Program, participants visit SNOLAB, a particle physics lab located deep underground in Sudbury, Ontario.

“Bright Minds in Their Life’s Prime“

Hip hop and theoretical physics are rarely mentioned in the same sentence, let alone in rhyming verses.

But Shad is a rare kind of rapper, whose linguistic dexterity and infectious rhythms are matched by his sense of intellectual adventure. So he didn’t flinch when asked to write and perform an original spoken-word piece for the ceremony celebrating the 2014 class of Perimeter Scholars International (PSI), the Institute’s master’s program.

“I couldn’t turn it down,” he recalls of the request from Perimeter Director Neil Turok, whom Shad had befriended several months earlier at an event in Calgary where both were invited speakers.

Inspired by Turok’s latest book and a personal tour of Perimeter, Shad performed a piece called “The Nature of Light” at the June 21 PSI celebration. A few hours before he took the stage, Shad sat down with *Inside the Perimeter* to chat about creativity, the scientific process, and the unexpected magic that can happen when they collide.

Inside the Perimeter: So have you ever performed at a theoretical physics research institute before?

Shad: Let me think about that for a second ... Nope! (laughs) It’s an interesting partnership. But I like finding inspiration from places that are a little distant from my own place. I find Neil to be an inspiring guy, and his faith in hard work and collaboration and good people and good science – it’s all very inspiring. When I was walking around Perimeter, trying to make sense of what I saw on the blackboards, it was amazing.

Inside: Were you able to make sense of it?

Shad: I’ve never taken a physics class, but Neil was able to explain it in terms I understand, like the mathematics underlying music. I think there’s a deep similarity. When you’re writing music, you sometimes get a sense, an intuition, that you’ve struck on the right thing – the right poetry, or the right music. It’s the same in physics and math: the search for the true nature of reality, the simplicity that might be hidden there. I’m interested in that idea, that the nature of reality may be quite simple and we can grasp it through intuition and creativity and hard work.

Inside: Do you see similarities between what you do and what happens at Perimeter?

Shad: I think there’s a science to art, and there’s an art to science. There’s definitely an aspect of imagination in good science, just like there is in art. There’s a level of mastery you could call artful in science. You bring reason to bear in both, but also passion and imagination. You need those intangibles, which most people relate to art, to make breakthroughs in science.

Inside: Your lyrics are known for their intelligence and positivity, which are sometimes lacking in hip hop. Why is it important for you to write at a higher level?

Shad: There’s an aspect of responsibility I’ve always felt with music. You’re asking for people’s attention, so you should say something worthwhile, something of value. I think that’s what I have to offer as an artist. I see my responsibility as having something worthwhile to say that’s positive and insightful.

Inside: Might your next album have a song about theoretical physics?

Shad: You never know! (laughs) I’m always trying to push myself, push my talent, push my courage, and trying to do something different, something better. I see that happening here – a sense of wonder at what we can achieve in our thinking, in building knowledge upon knowledge.

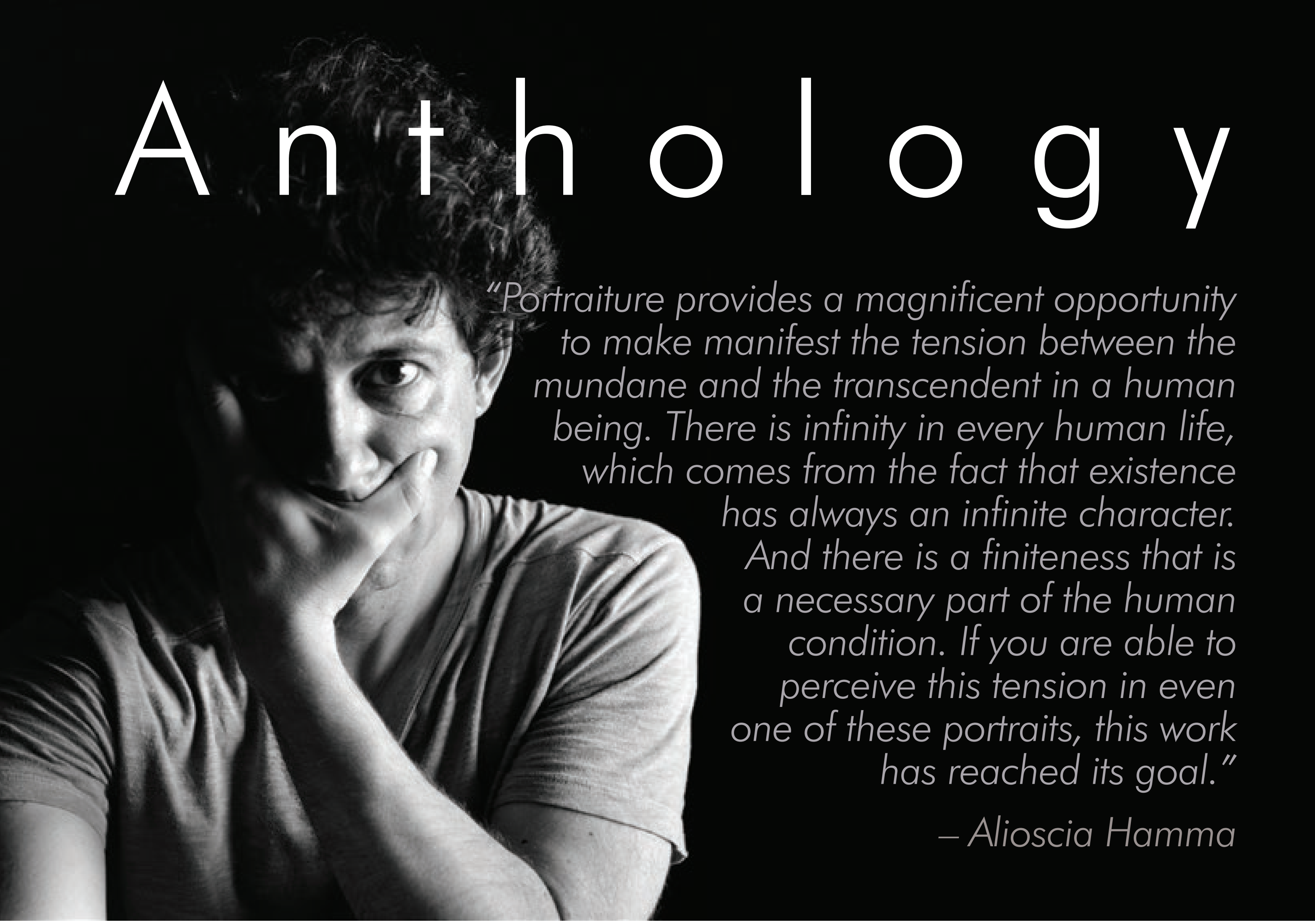
– Interview by Colin Hunter

The Nature of Light (Excerpt)

By the lights that guide your minds – that's how science advances.
Make your light the clearest, with the purest intentions:
courage and strength and perseverance
To search and to sense and to further inventions
And to flourish in a world with a curious penchant,
A worrisome tendency to hurry to secure some attention,
To seek personal fame first and personal gain.
It's the same in entertainment, but such work is in vain.
Be encouraged to work together with purpose, in service for change,
To build the pillars and furniture and the terms to explain
The ways that nature is structured, with strong frameworks to sustain
A place to gain further knowledge of the universe,
through the universe in your brains.

When I do a verse, it's to help me stay in my right mind
And to gain sight, as most stumble through the night blind.
And I'm seeing signs, more lights shining from bright minds
In their life's prime – this feels like once in a lifetime,
Like maybe we can do better than building pipelines
Or fighting over conflict diamonds in Wolframite mines
And we can do more than just retweet or even write rhymes.
We can write history – right now is the right time.

– Shad



A n t h o l o g y

"Portraiture provides a magnificent opportunity to make manifest the tension between the mundane and the transcendent in a human being. There is infinity in every human life, which comes from the fact that existence has always an infinite character. And there is a finiteness that is a necessary part of the human condition. If you are able to perceive this tension in even one of these portraits, this work has reached its goal."

– Alioscia Hamma

Our perception of time as both a series of moments and as a continuous stream is inherent to our everyday experience – and, of course, to the study of quantum gravity. Both life and gravity are of great interest to physicist and photographer Alioscia Hamma, who was just three when he took his first picture with a 1955 Russian Zorki camera. "Incidentally," he says, reflecting on that first moment of freezing time, "that is also my earliest memory."

He has been taking pictures ever since.

Hamma shot the portraits in the following pages with an old Rolleiflex camera – the kind that records images on film, rather than a digital chip. "I think it looks better. It also slows me down and makes me think," he explains.

At three years old, Alioscia Hamma took his first photo with a 1955 Russian Zorki camera.

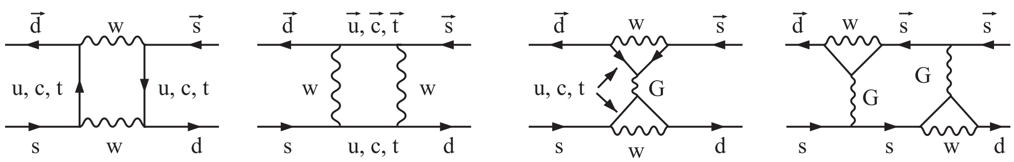
When shooting these portraits, Hamma asked each sitter to bring a text "of some importance" to them and to read it prior to his taking the portrait. They came with poetry, classics, rock and roll lyrics, and technical papers. There was one self-help book. Although Hamma had initially thought the texts would simply be a way of putting his subjects at ease, he soon realized that they were integral to the portraits.

Hamma took 24 portraits at Perimeter, where he was a postdoctoral researcher in quantum gravity from 2008 to 2013. He has since taken 20 more at Tsinghua University in Beijing, where he is now an assistant professor. His hope is to collect 100 portraits and accompanying texts into a volume he calls *Anthology*, a set of discrete moments out of which something larger and more fluid can emerge.

– Natasha Waxman

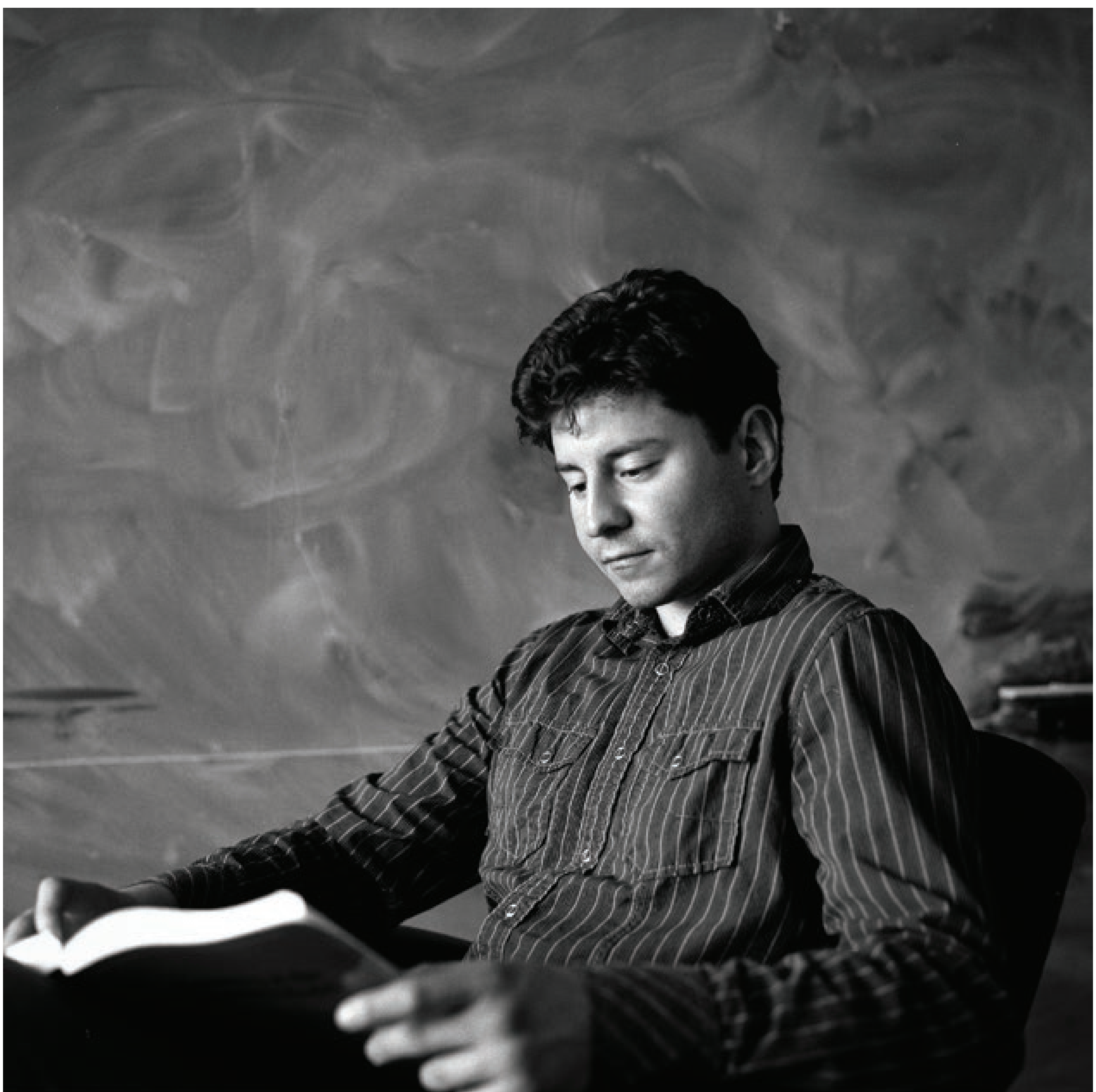
"Kaon Mixing and CP Violation"

The factors η_1, η_2 and η_3 are QCD short-distance renormalization factors analogous to the renormalization group coefficients for the $\Delta S = 1$ hamiltonian discussed in the previous chapter. For $m_t > M_W$, $\Lambda_{QCD} \simeq 200$ MeV.



Dynamics of the Standard Model (Cambridge Monographs on Particle Physics, Nuclear Physics and Cosmology),
J.F. Donoghue, E. Golowich, B.R. Holstein, Cambridge University Press, 1992.

Gordan Krnjaic, Postdoctoral Researcher at Perimeter Institute



Nosiphiwo Zwane, Graduate Student at Perimeter Institute

"Quantum Regrets"

It should be noted that quantum mechanics has had many detractors including the noted physicists Albert Einstein, Boris Podolsky, Nathan Rosen, Erwin Schrödinger, Max Planck, Max von Laue, and Alfred Lande among others. The feeling, thoughts, intuitions, and general logic of these physicists inclined them to feel that there was something right and correct about quantum mechanics, but in the end there was something fundamentally wrong as well. Even Richard Feynman, awarded the Nobel Prize for advancing the theory of quantum electrodynamics, had his doubts about quantum mechanics, so one shouldn't feel blasphemous in questioning it. Feynman is quoted as saying, "We have always had a great deal of difficulty understanding the world-view that quantum mechanics represents. At least I do, because I'm an old enough man that I haven't got to the point that this stuff is obvious to me. Okay, I still get nervous with it … You know how it always is, every new idea, it takes a generation or two until it becomes obvious that there's no real problem. I cannot define the real problem, therefore I suspect there's no real problem, but I'm not sure there's no real problem."

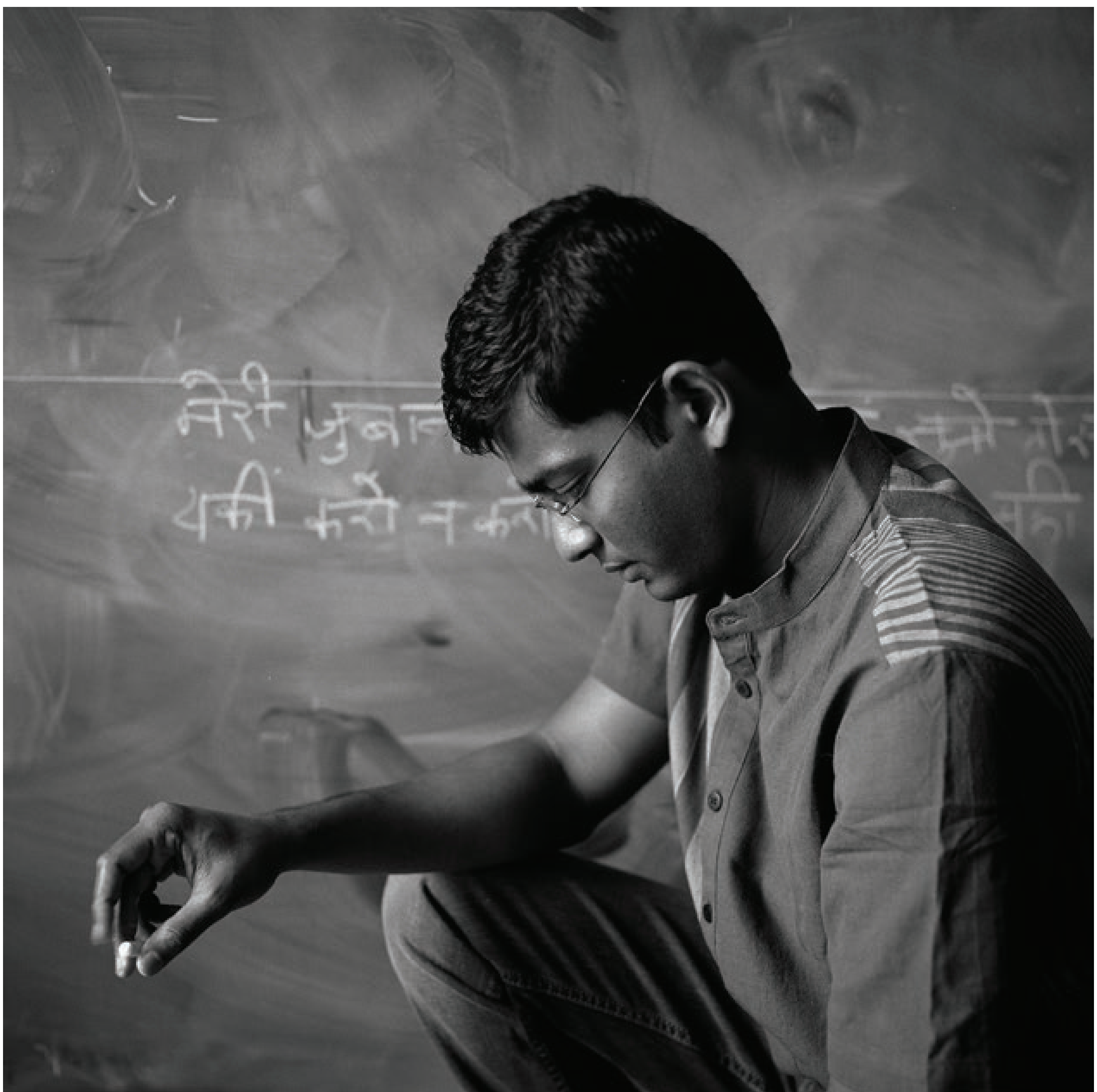
Excerpt from *Quantum Mechanics – What is wrong with it and how to fix it*
by Janeen Hunt, Lulu Publishing, 2006

Meri Zubaan se Meri Dastaan Suno to Sahi

My story in my own words, pray, listen to it;
Whether you believe it or not, Thou Merciful! at least, listen to it.
Let me agree that I am a culprit of love;
My confession of my crimes, at least, listen to it.
My friends, you too, will turn enemies one day;
The sorrowful cry of my life, at least, listen to it.
The people in this gathering of the world, who sit with their lips sewn;
Their silence, at least sometime, pray, listen to it.
You will allege time to be the culprit, even in the bloom of spring;
How my home was consumed by fire! pray, listen to it.

– Sudarshan Faakir

Siddhartha Santra, former PI Visiting Graduate Fellow, now a Postdoctoral Researcher at the U.S. Army Research Laboratory, Adelphi, Maryland



Héctor Bombín, former PI Postdoctoral Researcher, now at the University of Copenhagen

autumn passes -
for me no gods
no buddhas

– Masaoka Shiki
Translated by Burton Watson

"On Tree Amplitudes in Gauge Theory and Gravity"

We close with brief comments on some possible implications of our results. The ability to use BCFW recursion relations to compute higher-dimensional amplitudes can be useful for computing certain massive 4D amplitudes where the massive particles can be thought of as KK modes in the dimensional reduction of the higher-dimensional theory (other extensions of recursion relations to include massive particles have been discussed in [25, 26]). This can be used for the analytic computation of some massive SM amplitudes of relevance to the LHC.

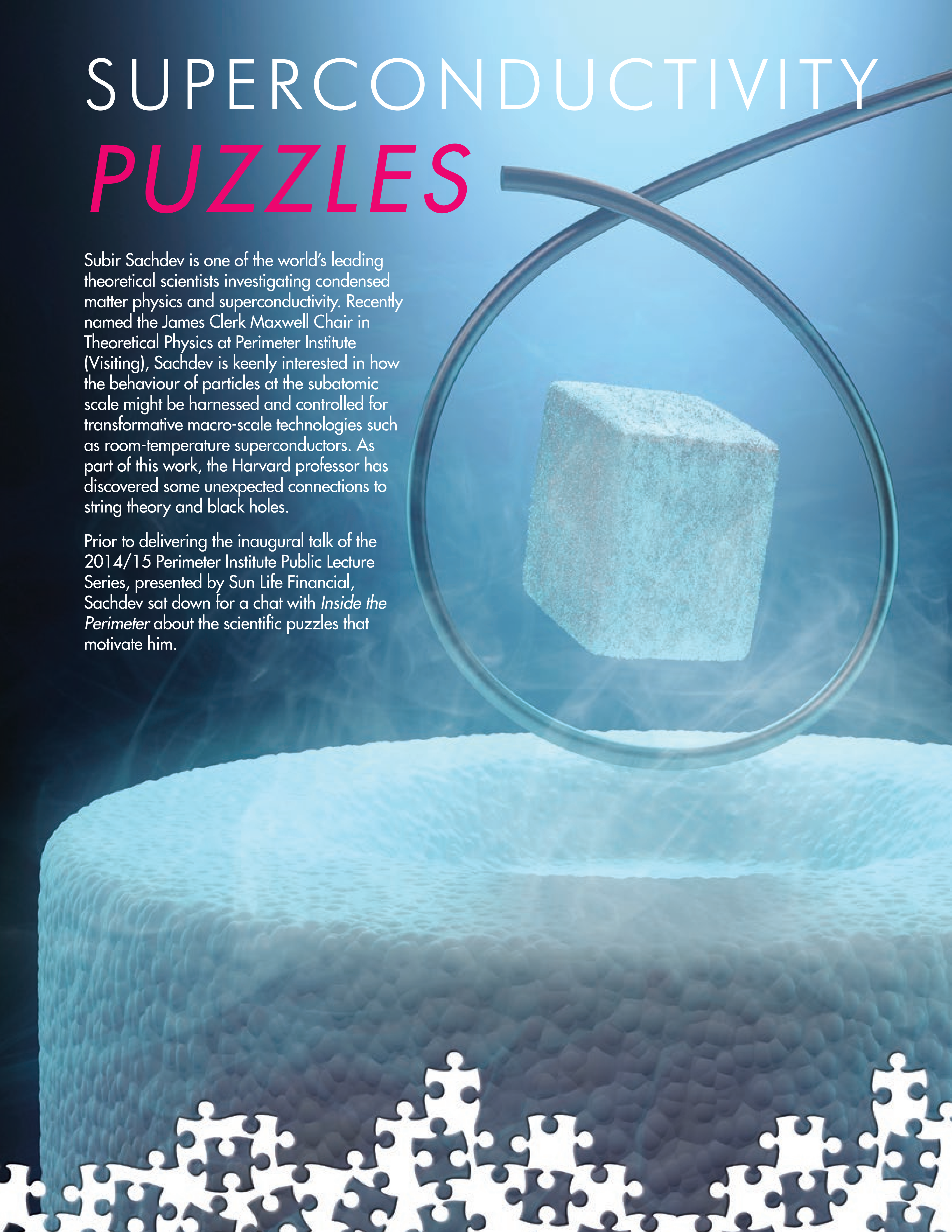
– Nima Arkani-Hamed and Jared Kaplan, published in *JHEP* 0804 (2008) 076, arXiv:0801.2385.

Sayeh Rajabi, former PI Graduate Student, now a Postdoctoral Fellow at the University of Waterloo

SUPERCONDUCTIVITY *PUZZLES*

Subir Sachdev is one of the world's leading theoretical scientists investigating condensed matter physics and superconductivity. Recently named the James Clerk Maxwell Chair in Theoretical Physics at Perimeter Institute (Visiting), Sachdev is keenly interested in how the behaviour of particles at the subatomic scale might be harnessed and controlled for transformative macro-scale technologies such as room-temperature superconductors. As part of this work, the Harvard professor has discovered some unexpected connections to string theory and black holes.

Prior to delivering the inaugural talk of the 2014/15 Perimeter Institute Public Lecture Series, presented by Sun Life Financial, Sachdev sat down for a chat with *Inside the Perimeter* about the scientific puzzles that motivate him.



Inside the Perimeter: What questions keep you up at night?

Subir Sachdev: I spend most of my time thinking about properties of materials and wondering why they behave the ways they do. Why is a piece of copper such a good conductor of electricity? Why is diamond transparent and a good insulator? Why is silicon a semiconductor, which is crucial for modern electronics? These sorts of simple questions have been well answered, and the answers, somewhat surprisingly for materials at macro scales, rely on quantum physics – on understanding the behaviour of literally trillions of electrons in these materials, moving cooperatively through the crystal or wire or whatever it may be. You immediately face the question of how to understand the quantum mechanics of so many electrons.

Inside: That sounds daunting.

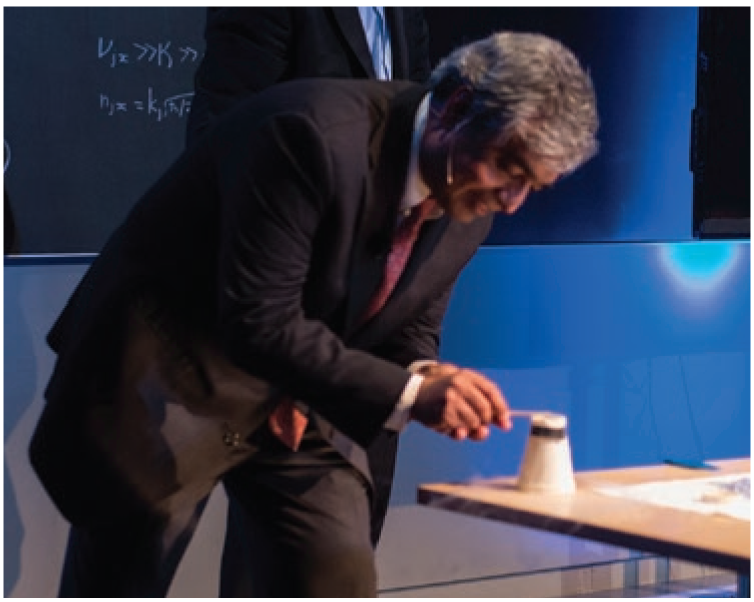
Sachdev: A lot of new concepts have been developed, and there's a lot of intellectual excitement. These also – remarkably – apply to somewhat rarer materials today, but which perhaps may not be so rare in the future.

Inside: Can you give an example?

Sachdev: One is yttrium barium copper oxide, or YBCO, which involves many elements arranged in a complicated structure. This particular material is a superconductor, meaning that it conducts electricity … with essentially no resistance and no loss of power. But there's one condition – you have to cool it, to a point on the order of the boiling point of liquid nitrogen. If you took a crystal of YBCO and put it into liquid nitrogen, it would start to superconduct. It raises questions as to why and the answers lie in quantum mechanics. So I work on understanding new phases of electrons that emerge when you have to treat them together, which requires understanding quantum mechanics in a very new regime.

Inside: Why are superconducting materials so significant?

Sachdev: Transmitting electricity with no losses or resistance allows superconductors to create very large magnetic fields. One place you might experience such a field is in an MRI machine. When you're in the machine, you're actually surrounded by a very large magnet. And all the noise that you hear is really just the noise of the magnet heating up and vibrating because of all the current you have to send into the magnet to create that magnetic field. But if you had a superconductor, you could get much larger magnetic fields with much less loss and a much smaller mode of power, which increases the precision of your MRI images. There are also various trials on using superconductors to transmit electric power with much less loss, and much smaller cable.



Theory in Action: *Subir Sachdev gave a riveting, and at times hilarious demonstration of superconductivity during his recent Public Lecture at PI. View the entire talk at www.perimeterinstitute.ca.*

Inside: What's the biggest hurdle to creating superconductors that don't need to be cooled?

Sachdev: If I knew the answer to that, I'd be winning many prizes! [laughs] That's the main question of the field: Why can't you just get rid of the liquid nitrogen and get a superconductor at room temperature? If you could, certainly the number of applications would explode. I don't think anybody knows, but there doesn't seem to be any reason why it's impossible. It's a matter of finding the right environment for the electrons for them to superconduct at room temperature. The reason it's so difficult is that you have to really understand the collective behaviour of trillions, nearly an infinite number, of electrons together. That's not easy.

Inside: Your research into these questions has also led you in unexpected directions, right?

Sachdev: Work that I've been involved in has found a connection to string theory and black holes and gravitational physics – that was completely unexpected! That turns out to be important in a peculiar situation that arises in something called a quantum phase transition. Near a quantum phase transition, you get a very peculiar type of entanglement which has a long-range character. The mathematics of that long-range entanglement turn out to be similar, quite amazingly, to the nature of entanglement near the horizon of a black hole. If you had told me this 10 years ago, I would have said you're crazy – this doesn't make any sense. But that's one of the things I've played some part in developing. We are trying to translate the language of these two fields to each other and learn more about quantum phase transitions in condensed matter from these methods in string theory.

Inside: You seem excited to keep digging.

Sachdev: It's like solving a puzzle – I enjoy it. I talk to experimentalists who have seen these strange phenomena and I've had some success in explaining a bit of it. That gives you a taste, and then you always want to solve more. There's a lot of fun in solving these puzzles, even taking baby steps.

Inside: Have you always been a puzzle-solver?

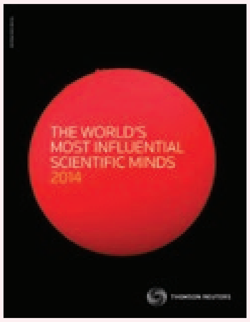
Sachdev: I always enjoyed physics and mathematics, so my parents, like most Indian parents, said I should be a computer engineer or a doctor. So I followed that track for a while, but on the side I was reading about the history of quantum mechanics. I particularly enjoyed the books of Richard Feynman – they really got me hooked. I didn't want to just play with devices – I really wanted to understand what was going on inside.

– Interview by Colin Hunter

Schuster and Toro Win New Horizons Prize

Perimeter Faculty members Natalia Toro and Philip Schuster have been awarded a 2015 New Horizons in Physics Prize "for pioneering the 'simplified models' framework for new physics searches at the Large Hadron Collider, as well as spearheading new experimental searches for dark sectors using high-intensity electron beams." Awarded by the Breakthrough Prize Foundation, the prestigious $100,000 prize recognizes exceptional young theorists who are "dedicated to advancing our knowledge of the universe at the deepest level." Schuster and Toro's selection marks the third year in a row that Perimeter faculty members have been recognized, following Freddy Cachazo and Davide Gaiotto.

PI Researchers Named Among "World's Most Influential Scientific Minds"



Perimeter Faculty members Robert Myers and Subir Sachdev were named among the world's most influential scientific minds, according to a recent study. Thomson Reuters analyzed citation data over the last 11 years to identify scientists whose publications ranked among the top one percent most cited for their subject field and year of publication, thereby having the greatest impact on the future direction of their fields. Other Perimeter researchers acknowledged in the Physics category included Distinguished Visiting Research Chairs Lance Dixon and Dam Thanh Son. To see the full list, visit www.highlycited.com.

Turok Honoured in Canada and South Africa

In recognition of his pioneering research in cosmology and his efforts to advance science both in Canada and worldwide, Perimeter Director Neil Turok has been elected to the Royal Society of Canada. Fellows are "peer-selected as the best in their field," in areas spanning science, the arts, and Canadian public life. The Royal Society of Canada has celebrated the work of exceptional Canadians for the past 130 years. Turok was also recently honoured by three universities – Nelson Mandela Metropolitan University and Rhodes University, both in South Africa, and Saint Mary's University in Halifax – which awarded him honorary doctorates as part of their convocation activities.

Martin-Martinez Wins Polanyi Prize

Perimeter Visiting Fellow Eduardo Martin-Martinez has earned one of five John Charles Polanyi Prizes from the Council of Ontario Universities. Given each year to exceptional young researchers in the fields of physics, chemistry, physiology or medicine, literature, and economic science, the Polanyi Prizes aim to recognize work with great potential to advance their respective fields and are worth $20,000. Martin-Martinez works in the young field of relativistic quantum information, studying gravity's effects by combining strands of quantum information science with quantum field theory and general relativity. The Prizes are named for Nobel Prize-winning Hungarian-Canadian chemist John Polanyi.

Perimeter Launches Tensor Networks Initiative

In October, Perimeter announced the Tensor Networks Initiative, aimed at building a node of world-leading expertise in tensor networks – a new approach used in condensed matter physics, quantum information, and other fields. The initiative will be led by Perimeter Faculty member Guifre Vidal, a pioneer in the area, and will involve other Perimeter researchers, including Bianca Dittrich, Zhengcheng Gu, and Roger Melko. The program, projected to run for five years, will facilitate collaboration visits from Distinguished Visiting Research Chairs and Visiting Fellows. Several postdoctoral researchers will also be hired in the area, and regular workshops and summer schools will be held to share results with the wider scientific community. More information is available at www.perimeterinstitute.ca.

Perimeter Welcomes Three New DVRCs

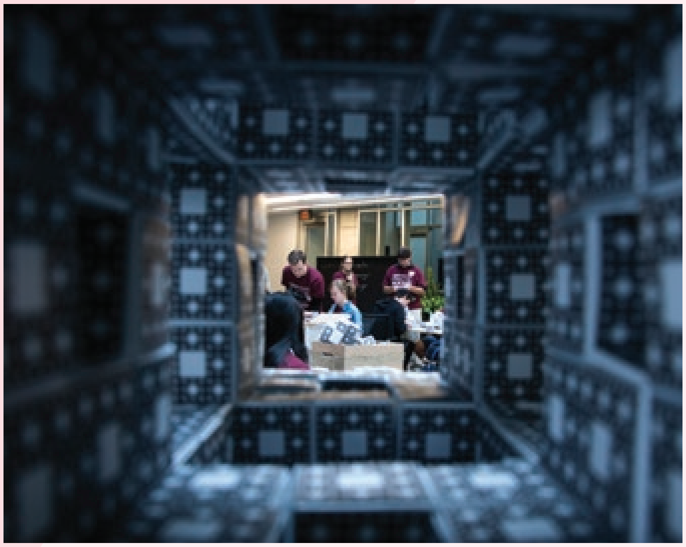
Perimeter has recently appointed three new Distinguished Visiting Research Chairs (DVRCs). DVRCs are eminent scientists who make the Institute their second research home, spending extended periods at Perimeter while retaining permanent positions at their home institutions. The new DVRCs are

Gabriela Gonzalez (Louisiana State University), spokesperson for the LIGO Scientific Collaboration and an expert in gravitational wave detection; Frank Verstraete (University of Vienna and Ghent University), a quantum physicist focused on quantum information theory and quantum many-body physics; and Matias Zaldarriaga (Institute for Advanced Study), a leader in the study of the cosmic microwave background and the large-scale structure of the universe. In addition to the new appointments, Perimeter has renewed the terms of five DVRCs – James Bardeen, Ganapathy Baskaran, Frans Pretorius, Gerard 't Hooft, and Senthil Todadri – through 2017.

… And Seven New Visiting Fellows, While We're At It

Much like DVRCs, Visiting Fellows span a wide range of expertise and retain their positions at home institutions while making extended research visits to Perimeter – in their case, of up to six months each year. Perimeter appointed seven accomplished researchers as Visiting Fellows in recent months: Philippe Corboz (University of Amsterdam), Fay Dowker (Imperial College, London), Jerome Gauntlett (Imperial College, London), Jutho Haegeman (Ghent University), Si Li (Mathematical Sciences Centre at Tsinghua University), Eduardo Martin-Martinez (Institute for Quantum Computing at the University of Waterloo), and Brian Swingle (Stanford University). The Institute also renewed the appointments of Jonathan Barrett, Ruth Gregory, and Kris Sigurdson through 2017.

Math + Arts & Crafts = MegaMenger!



Local students and Perimeter staff joined forces in October to help create what just may be the world's biggest fractal model. Perimeter was one of 20 sites worldwide to participate in the MegaMenger Project, which created a Level-4 Menger Sponge – a three-dimensional fractal made up of smaller cubes in a repeating pattern. Nine Waterloo Region schools, involving nearly 400 students, used 48,000 business cards to construct 8,000 Level-1 Menger Sponges, which were then assembled into a Level-3 sponge by Perimeter staff and student representatives. The completed Level-3 sponge is part of a giant Level-4 sponge, spread around the world. Visit www.youtube.com/PIOutreach to view a timelapse of the MegaMenger build.

Four Faculty Receive Early Researcher Awards

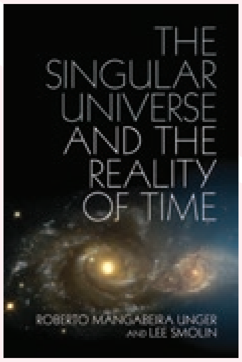
Four of Perimeter's youngest faculty members were among those honoured by the Province of Ontario with Early Researcher Awards: Dmitry Abanin, Bianca Dittrich, Davide Gaiotto, and Natalia Toro. The Early Researcher Awards are intended to support highly promising early-career faculty in building their research teams – including graduate students, postdoctoral fellows, research assistants, and associates – with $140,000 grants.

AIMS-Tanzania Opens

In October, Perimeter's primary global outreach partner, the African Institute for Mathematical Sciences (AIMS), opened its fifth centre of excellence, in Tanzania, as part of the Next Einstein Initiative (NEI). AIMS-Tanzania opened at a temporary site in Arusha, with a permanent campus in Bagamoyo set to open in the fall of 2015, following extensive renovations. AIMS was founded in 2003 by Perimeter Director Neil Turok, and Perimeter has lent expertise in support of the AIMS-NEI network since his arrival at the Institute in 2008.

Now, Then, and Everything in Between

It is present everywhere, yet untouchable. It defines everything, yet resists definition: Time.



The Singular Universe and the Reality of Time, by PI Faculty member Lee Smolin and Harvard philosopher and legal scholar Roberto Mangabeira Unger, offers a new consideration of time, which is eternally vexing in many arenas of human thought – nowhere more so than in physics.

The book is impelled by a crisis the authors perceive in fundamental physics and cosmology. A key to resolving it, they propose, is to consider the hypothesis that the laws of physics evolve in time.

Smolin says he has been thinking about these ideas since the late 1980s, when his friend Andrew Strominger (a physicist at Harvard and a Perimeter Distinguished Visiting Research Chair) told him about the vast catalogue of string theories. Inspired by evolutionary theory, Smolin postulated physical laws evolving over time through mechanisms analogous to biological natural selection. Years later, he discovered that Unger shared similar views and their eight-year collaboration began.

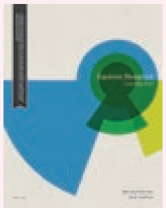
While most physicists believe that time "emerges" as a consequence of (timeless) physical laws, the new book posits instead that time is the most fundamental aspect of reality. There are provocative implications for fundamental physics, as well as mathematics. At the very least, the book will provoke discussion and reflection on what it means to aspire to extend the reach of science to the universe as a whole.

The Singular Universe and the Reality of Time is published by Cambridge University Press.

Serbinis Joins the Board

Perimeter welcomes visionary entrepreneur Michael Serbinis to its Board of Directors. Serbinis is currently founder and CEO of The Everlong Project, a digital health startup launching in 2015. He was also the founder and CEO of Kobo, a digital reading company that achieved $110 million in sales in its first year and amassed 20 million customers in 190 countries. He has built several other transformative technology platforms for various industries, including a quantum cryptography system and a high temperature superconductor propulsion system that won numerous awards. Serbinis is currently the founder of Three Angels Capital and a member of the Board of Trustees at the Ontario Science Centre. He holds a BSc in engineering from Queen's University and an MSc in industrial engineering from the University of Toronto.

WGSI Releases Equinox Blueprint: Learning 2030



The Waterloo Global Science Initiative (WGSI) recently released its Equinox Blueprint: Learning 2030, a vision for redesigning high school education to best prepare students for the challenges and opportunities of the 21st century. WGSI is a non-profit partnership between Perimeter Institute and the University of Waterloo, created to promote dialogue around complex global issues and advance strategies for a sustainable future. The Blueprint represents the comprehensive findings and recommendations for rebooting high school education that resulted from a week-long forum of more than 40 education innovators, held at Perimeter in 2013. The full document can be downloaded at wgsi.org.

Donor Profile: **Amy Doofenbaker**

Amy Doofenbaker's connection to Perimeter Institute was forged in an unlikely scenario: during the veterinary examination of a dog.

The veterinarian was Doofenbaker herself – Doc Amy, as she is known to clients of her mobile veterinary service – and the dog was the beloved companion of a Perimeter Institute volunteer. The topic of theoretical physics came up in conversation during the examination ("How exactly it came up, I have no idea," laughs Doofenbaker), and the doctor's eyes lit up as her client described Perimeter's popular Public Lecture Series.

Doofenbaker already had an avid interest in theoretical physics – the bookshelves of her home overflow with the works of Richard Feynman, Roger Penrose, Sean Carroll, Max Tegmark, and other physics communicators – so she was overjoyed to learn that free public lectures were being held at the Institute every month.

The two-hour drive due south to Waterloo from her home in the rural Ontario community of Chesley was no deterrent; she immediately began attending lectures and was thrilled to see, and even chat with, some of the "physics icons" whose works had captivated her mind for years.

"I was so excited to come to the public lectures," she recalled. "Being around other people who share my enthusiasm for science is wonderful."

Her experiences at Perimeter have been so profound and inspiring that she has become a legacy donor to Perimeter, leaving a gift to the Institute in her will. She considers it a poignant, enduring way to "be part of the adventure that is unravelling the mysteries of the universe."

Learning about the mysteries and wonders of the universe is more than a hobby for Doofenbaker. In many ways, it has been a lifeline – a way to make her "mind dance" when her body was incapacitated.

Doofenbaker could have lost her leg, and her life, when gangrene set in after surgery to repair a knee she injured in a skiing accident at age 14. She endured many surgeries and considerable time in traction, and required crutches to walk for years.

Though her body was often confined to a hospital bed, her mind could soar anywhere books could take her. She started with philosophy, then moved on to general science books, and then became captivated by physics after reading the books of Richard Feynman and Leon Lederman (the latter sparking her over-20-year fascination with the Higgs boson).

Even as her leg recovered from multiple surgeries and she regained the ability to walk, reading about physics fed her insatiable curiosity about the inner workings of the universe. "The more I study, the more obvious it becomes how little I know," says Doofenbaker. "It makes me driven to learn more."

When she discovered Perimeter in 2010, she was inspired not only by the fundamental research conducted at the Institute, but also by its commitment to sharing the power of science with the world through education and outreach.

As a woman who overcame many challenges to pursue her passion for veterinary medicine, Doofenbaker is inspired by female scientists such as Marie Curie, Dorothy Hodgkin, and Rosalind Franklin, who transcended barriers in pursuit of their scientific passions. She strongly believes in and supports Perimeter's Emmy Noether initiatives, which, in honour of their mathematician namesake, provide opportunities and encouragement for young women to pursue careers in physics.

She also shares Perimeter's vision for the power of scientific outreach. When the 2014/15 season of the Perimeter Institute Public Lectures Series, presented by Sun Life Financial, launched in October, Doofenbaker was among the first in line, and was energized by Subir Sachdev's talk about quantum entanglement and superconductivity.

"What I see at Perimeter is people who share my passion," she says. "I see wonder and awe and joy for science – that's so exciting to be a part of."

A perfect day, she says, involves tending to her clients and their beloved pets, before spending the evening reading a physics book with her own cat curled up on her lap. If the mood strikes, she'll play the violin she built from scratch (a picture of Albert Einstein playing violin is affixed to her music stand for inspiration).

Doofenbaker's passion for physics even took her to CERN in Switzerland, home of the Large Hadron Collider, where she was given an extensive tour of the facility and connected with several physicists. The visit was coupled with another poignant milestone in her life: skiing in the Alps.

Decades after the skiing accident that radically changed her life, Doofenbaker took up sit-skiing, and the trip to CERN gave her the perfect opportunity to achieve the dream of carving down the Swiss Alps.

Whether applying the principles of Newtonian physics while swooshing downhill or pondering the concepts of theoretical physics at home, Doofenbaker finds fulfillment in connecting with the forces of nature.

"I always want to keep my mind dancing with ideas," she says. "Perimeter epitomizes the characteristics most important to me: creativity, awe, passion, and curiosity."

– Colin Hunter

Pizza!

Who doesn't love pizza? Not Black Hole Bistro Head Chef Ben Uniac: "My favourite is mango and prosciutto with goat cheese — a play on Hawaiian. But even a basic pizza with tomato sauce and mozzarella cheese can be amazing."

Here's the chef's recipe for pizza dough à la the Black Hole Bistro:

Ingredients

- 3 cups (750 mL) all-purpose flour
- 2 tsp (10 mL) quick-rising instant dry yeast
- 1 tsp (5 mL) sugar
- 1 tsp (5 mL) salt
- 1 ¼ cups (300 mL) warm (120°F/50°C) water
- 2 tbsp (15 mL) extra virgin olive oil

Preparation

Preheat the oven to 500°F. (If you have a pizza stone, heat the stone too.)

In a bowl, combine 2 ¾ cups (675 mL) of the flour, yeast, and salt. (Hold back the other ¼ cup of flour for now.) With a wooden spoon, gradually stir in water and oil until ragged dough forms, using your hands if necessary.

Turn the dough out onto a lightly floured surface; knead for about eight minutes or until smooth and elastic, adding the extra ¼ cup of flour only if you need to. Add just one tablespoon at a time.

Pour the olive oil into a bowl, then put the ball of dough in and turn it to grease it everywhere. Cover the dough with plastic wrap; let rise in a warm, draft-free place until doubled in bulk, about 1 hour. (*Make-ahead: Refrigerate unrisen dough and let rise for 24 hours. Or freeze in a plastic bag for up to one month, and let thaw and rise in refrigerator overnight.*)

Roll the dough out to roughly 14 inches in diameter. Transfer it to your pizza stone or to a cookie sheet — ideally a round one. To make transferring easier, try rolling the dough around your rolling pin and unrolling it onto the stone.

Spoon on the sauce and sprinkle with mozzarella, then evenly scatter whatever toppings you like.

Bake at 500°F for about 15 minutes, or until the crust is golden and the cheese is lightly browned.

Why Do We Fold Pizza?

When eating one of the delicious pizzas described on page 40, you may find the tip of your pizza wedge drooping toward the floor like a particle into a potential well. To counteract that, we recommend something the foodie scientists at Serious Eats have dubbed "The Fold Hold." Bending the crust end of the pizza into an arc keeps the pointed end from pointing down.

But why? How can introducing a bend in one axis create rigidity in the other axis?

Physicists (and probably only physicists) will not be surprised that the mysterious stiffness of folded pizza answer involves a foundational result in differential geometry: Gauss' "Remarkable Theorem" (he really called it that). The Remarkable Theorem says that if you take a surface (or a piece of pizza) and bend it without stretching or tearing it, its Gaussian curvature stays the same.

What's Gaussian curvature? It's a little complex to define when your hands are covered with cheese grease, but basically it's the number you get when you multiply the curvature of one axis together with the curvature of the other axis. Sheets and tubes have a Gaussian curvature of zero, spheres and eggs have a positive curvature, and saddles and Pringles chips have a negative curvature.

Thus, if you bend your pizza in one axis, the other axis has to stay straight – at zero curvature – so that the Gaussian curvature stays at zero.

The related question of why you can't gift wrap a bowling ball is left as an exercise to the reader. Finish your pizza first! [i]

[i] Finished already? And you really want to know why you can't gift wrap a bowling ball? The Remarkable Theorem says that a surface can only be wrapped or stretched or shrunk into another surface if the beginning surface and the ending surface have the same Gaussian curvature. You can turn a sheet of paper into a tube, because planes and tubes both have the same curvature. You can't turn a sheet into a sphere – or a sphere into a sheet – because they have different curvatures. This is why you can't gift wrap a bowling ball, and why you can't flatten an orange peel without breaking the peel. Also: Greenland is smaller than you may think.

PI KIDS ARE ASKING

Why do we blow on hot food?

I blow on my spaghetti and meatballs so I can cool it down faster. I'm hungry and I need to eat. But why doesn't the spaghetti cool down fast enough on its own?

Heat is energy. Something heats up when energy enters it, takes the molecules and atoms that make up that something, and makes them jiggle and move around faster. It's the molecules in the spaghetti and meatballs jiggling around really fast that make the food on your plate hot. As the energy goes away, the molecules slow down and the spaghetti gets cooler.

But where does the energy go? The answer is: into the air around it.

The energy of the jiggling spaghetti and meatball molecules excites the molecules in the air around the plate, making the air above your plate hotter while the spaghetti and meatballs get cooler.

But here's where things slow down: heat energy leaves an object faster when it has somewhere to go. With the molecules in the air around the spaghetti now full of energy, there's less room for the energy in the spaghetti to move into the air. Until the air around the spaghetti gives up its heat energy to the air further away from your plate, it's like a traffic jam of heat. Nobody at the back of the line can move until the molecules at the front of the line do.

Blowing over the top of your spaghetti and meatballs disturbs the air, pushing the excited air molecules away and bringing in molecules of cooler air that aren't as excited. Suddenly, there's room for more of the spaghetti's heat to move into the air, which it does, helping your meatballs get cool enough to eat.

Hot things cool faster when there's more places for their heat to go. The spaghetti all bundled up on your plate doesn't have all that much of itself touching the air. The heat in the centre of the pile of spaghetti has to get in line behind the heat of the spaghetti at the top of the pile before it can pass into the air. That's why another way to cool your spaghetti faster is to spread it around your plate. Give your spaghetti more surface area, and more air is available to take the heat away from your spaghetti.

PERIMETER PI INSTITUTE FOR THEORETICAL PHYSICS

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CLASSICAL WORLD ARTISTS *Series*

2014/15

CHRISTIAN TETZLAFF
SOLO VIOLIN
Wednesday, November 5, 2014

AVI AVITAL
MANDOLIN
Tuesday, December 2, 2014

BENEDETTO LUPO
PIANO
Thursday, February 5, 2015

SITKOVETSKY TRIO
Tuesday, March 3, 2015

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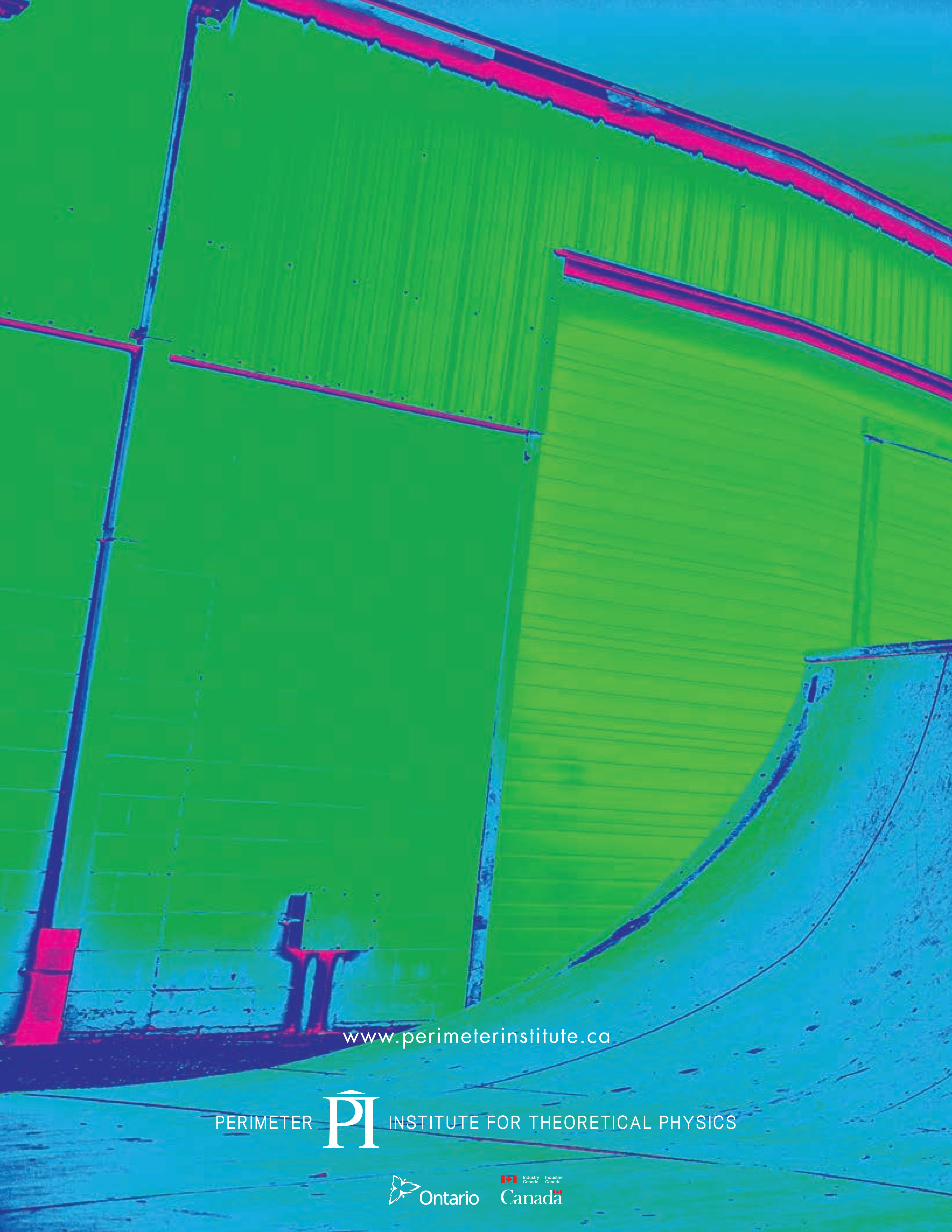

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