inside the Perimeter

spring/summer 2013

Condensed Matter
Xiao-Gang Wen Explores the "Frontier in the Middle"

Mathematical Physics
The New Face of Feynman Diagrams?

From the Black Hole Bistro
The Sweet Science of Chocolate

Plus ...
Special pull-out section:
The Process of Science

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

THE CBC MASSEY LECTURES

IDEAS

Pictured here, Perimeter Director Neil Turok delivers his final Massey Lecture in Toronto. In the fall of 2012, Turok delivered the five Massey Lectures to packed houses across Canada. If you missed them, you can read the collected lectures in *The Universe Within: From Quantum to Cosmos*, published by House of Anansi Press, or download them from iTunes. The whole series will be rebroadcast on CBC Radio this summer.

cbc.ca/ideas/masseyexperience

ANANSI CBC MASSEY COLLEGE PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

inside the Perimeter

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IN THIS ISSUE

Lead On: Neil Turok Reappointed

When Neil Turok arrived in Waterloo in October 2008 as Perimeter Institute's new director, it was a very different place. Our first permanent building had just opened, we had few students, and our faculty members still fit in one boardroom.

In his first five-year term as director, Turok launched the Distinguished Visiting Research Chairs program to attract world-leading scientists to Perimeter. He inaugurated the Perimeter Research Chairs, wooing Xiao-Gang Wen from MIT to become the first chairholder. He spearheaded the creation of the Perimeter Scholars International (PSI) master's program, a rigorous and innovative course designed to nurture a new generation of theoretical physicists. Under Turok's leadership, Perimeter has nearly doubled in size and expanded its scope of research into strategically chosen fields – you can read, for instance, about Perimeter's growing strength in condensed matter physics in this issue. In 2011, the new Stephen Hawking Centre officially opened, making this young institute the largest centre for theoretical physics in the world. Meanwhile, Turok himself was chosen as the 2012 Massey Lecturer.

It's been, in short, a great five years, and now Perimeter can look forward to five more.

Perimeter's Board of Directors has unanimously decided to reappoint Turok, with the full support of the faculty and the Institute's Scientific Advisory Committee. Turok will also become the inaugural Mike and Ophelia Lazaridis Niels Bohr Chair in Theoretical Physics.

Turok's new term as director commences in October 2013 and runs for an additional five years.

"When we invited Dr. Neil Turok to be Perimeter's director in 2008, we knew he was a world-class scientist and a visionary leader. What he has brought to the Institute in his first term as director has been nothing short of outstanding," said Board Chair Mike Lazaridis. "Under his direction, Perimeter has become one of the leading centres for theoretical physics in the world. It is also a special privilege for Ophelia and me to lend our name to this new Chair that will support Neil's world-leading research in early universe cosmology."

"I am humbled and excited by this news," said Turok. "I am especially honoured to be appointed as the first holder of the Mike and Ophelia Lazaridis Niels Bohr Chair and appreciative of the incredible support of Mike Lazaridis and the Board. Working with Perimeter's outstanding faculty and staff over the last several years has been intense, exciting, and hugely rewarding. Together, we are reinventing how theoretical physics is done. I can't wait to get started on the next five years."

- Natasha Waxman

Gaiotto and Hawking Awarded Fundamental Physics Prizes

Perimeter Galileo Chair Davide Gaiotto and Distinguished Visiting Research Chair Stephen Hawking were recently awarded prizes from the Fundamental Physics Prize (FPP) Foundation.

In contrast to the Nobel, which has a strong leaning toward tangible, quantifiable or practical discoveries, FPP prizes are intended to recognize theorists and researchers who are "dedicated to advancing our knowledge of the universe at the deepest level." Although new, these awards are already considered major distinctions.

Stephen Hawking was given one of two Special Prizes in Fundamental Physics – the other went to the Higgs boson team at CERN. Hawking was honoured for his discovery of Hawking radiation from black holes and for his deep contributions to both quantum gravity and the quantum aspects of early universe cosmology.

Gaiotto won a New Horizons in Physics Prize, which recognizes exceptionally promising young researchers.

Gaiotto, who is 35, does wide-ranging work – a sampling of recent paper titles includes "Pulling the straps of polygons," "Spectral networks," "Spectral networks and snakes," and "An E7 surprise." There are also references to wall crossings, knot invariants, superconformal indices, and three-manifolds. The young researcher is, in other words, the very model of a modern mathematical physicist.

Most of Gaiotto's work takes place at the intersection of quantum field theory and string theory. For instance, the textbook way we've always understood quantum fields is by writing down their Lagrangians and using standard mathematical tools to develop our understanding of the fields from there. In a breakthrough known as the "class S framework," Gaiotto used string theory tools to construct a huge class of quantum fields that do not depend on Lagrangians. It's as if all the quantum fields to this point were under a single lamp post – and Gaiotto lit up the rest of the street.

By vastly extending the canon of known field theories, Gaiotto provided a rare and potentially revolutionary glimpse into the structure of a generic field theory. The new framework set the stage for a flood of recent new results in quantum field theory and string theory, both from Gaiotto and from the broader research community. There were even unexpected payoffs in mathematics and mathematical physics. In developing the class S framework, Gaiotto discovered several results which are now being studied by mathematicians.

Gaiotto is currently pursuing a framework analogous to the class S framework for three-dimensional field theories. There are surprising connections to deep mathematics, including knot theory, three-manifold invariants, and cluster algebra. The physics payoff is the possibility of mapping out a large class for three-dimensional conformal field theories and computing their systemically protected properties.

This progress in our understanding of quantum field theories has broad potential, because quantum fields are essential to many areas of physics. Particle physicists use a quantum field theory called the Standard Model to precisely describe the behaviour of all known particles. Electronic engineers use a different quantum field theory to describe and design today's electronic devices. Condensed matter physicists use quantum field theories to describe superconductors and other exotic materials. Gaiotto's work could conceivably lead to deep mathematical advances, help us tailor exotic quantum systems to practical applications, or even advance our understanding of the fundamental laws of the universe.

"Perimeter Institute is thrilled that two of its researchers have been recognized with these major international awards," said Director Neil Turok. "Stephen's path-breaking discoveries about the quantum properties of black holes set the agenda for much of fundamental physics and cosmology over the past three decades. Davide's discoveries about quantum fields are likewise opening the way to more powerful mathematical descriptions of particles and forces in the universe."

- Erin Bow

Mike Lazaridis named Visionary of the Year

Perimeter Founder and Board Chair Mike Lazaridis has been named the 2013 Visionary of the Year by the Intelligent Community Forum (ICF), a New York-based think tank that studies how communities use information and communications technology. In discussing Lazaridis' selection, ICF Co-Founder Lou Zacharilla cited his entrepreneurial success with the invention of the BlackBerry, his contributions to Waterloo's world-class academic reputation, and his visionary support of local institutions, such as Perimeter Institute and the Institute for Quantum Computing. Lazaridis will accept the award and deliver an address at the ICF's annual summit on June 7.

Luis Lehner elected GRG Fellow

Faculty member Luis Lehner has been named a Fellow of the International Society on General Relativity and Gravitation (GRG) "for his contributions to computational gravitational physics, most notably in the areas of compact systems and their gravitational and electromagnetic signals, as well as gravity in higher dimensions." Lehner has done pioneering work investigating how gravity operates in extreme conditions such as black holes or neutron stars, and he has previously been elected as a Fellow of both the American Physical Society and the Canadian Institute for Advanced Research's program on Cosmology and Gravity.

Neil Turok receives honorary degrees

Perimeter Director Neil Turok was recently awarded honorary doctorates by Heriot-Watt University in Edinburgh, Scotland, and by the University of Guelph, in November 2012 and February 2013, respectively. Both institutions recognized Turok for his outstanding contributions to scientific research and his leadership in developing research excellence in Africa through the African Institute for Mathematical Sciences, Perimeter's global outreach partner.

Henry Reich launches *MinuteEarth*

Henry Reich, former PSI student and Film & Media Digital Artist-in-Residence, has launched a follow-up to his successful YouTube channel, *MinutePhysics*. Launched in March 2013, *MinuteEarth* is a new Youtube channel that aims to disseminate "science and stories about our awesome planet." The channel has already amassed more than 3.1 million views and 375,000 subscribers. Those interested in checking out Reich's latest speedy science endeavour can visit www.youtube.com/minuteearth or follow @MinuteEarth on Twitter.

Paige Murphy wins Luke Santi Award

Paige Murphy of Campbell River, British Columbia received the 2012 Luke Santi Memorial Award, presented annually by Perimeter to a Canadian high school student. Murphy received the BC Science Council Award and represented her school at both the Fermat Math Contest and the Physics Olympics at the University of British Columbia. In addition to her many extracurricular activities, Murphy won the RCMP Citizenship Award and has done volunteer work in Mexico and Kenya, as well as with the Salvation Army and Rotary Club International. She is now in her first year studying science at the University of Victoria.

Think like a physicist

In January 2013, Distinguished Visiting Research Chair Leonard Susskind published his third popular science book, *The Theoretical Minimum: What You Need to Know to Start Doing Physics*. Along with co-author and citizen scientist George Hrabovsky, Susskind guides readers through the basic skills required to tackle more advanced physics topics. Inspired by Susskind's popular Stanford University-based continuing education course, the book teaches readers how to think like a physicist without a university course.

S. James Gates Jr. awarded National Medal of Science

S. James Gates Jr., one of Perimeter's Distinguished Visiting Research Chairs, has been awarded the US National Medal of Science, the highest honour bestowed on scientists by the US government. Gates is one of the world's leading experts on supersymmetry, supergravity, and superstring theory, and he serves on President Barack Obama's Council of Advisors on Science and Technology. The Medals recognize extraordinary knowledge and outstanding contributions in science and engineering, and Gates was one of 12 scientists to receive the honour from President Obama in a White House ceremony on February 1, 2013. (See the insert in this issue for an article on how Professor Gates got his start in science).

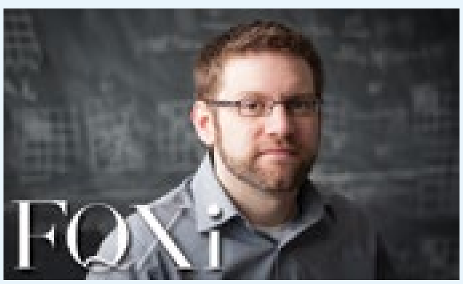
Melko and Vidal receive Templeton grant

Associate Faculty member Roger Melko and Faculty member Guifre Vidal have received a $450,000 grant from the John Templeton Foundation for their project, "Simulating Emergence in Quantum Matter." Melko and Vidal will use the grant to carry out large-scale computer simulations to explore the properties of emergence in lattice models of quantum matter. The project will span 2.5 years, and aims to advance our understanding of emergent phenomena in quantum matter and develop academic-licensed code to be used by specialists for further research.

Is time real?

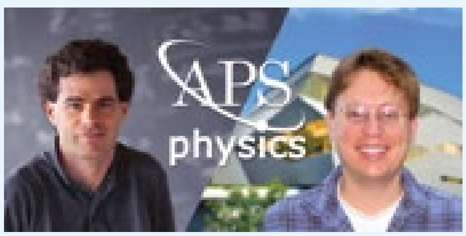
Faculty member Lee Smolin released his fourth popular science book in April 2013, *Time Reborn: From the Crisis in Physics to the Future of the Universe*. In it, Smolin digs into the notion long held among physicists that time is not real, but a human illusion in a timeless universe operating on predetermined laws. He outlines why he no longer holds this view and argues why accepting time as reality is one of the keys to producing better theories of the universe.

Robert Spekkens wins FQXi essay contest



Faculty member Robert Spekkens has won the $10,000 first prize in the fourth annual essay contest of the Foundational Questions Institute (FQXi). This year's theme was "Questioning the Foundations: Which of Our Basic Physical Assumptions Are Wrong?" Spekkens' winning essay, "The paradigm of kinematics and dynamics must yield to causal structure," suggests that we question the usual distinction between a physical theory's kinematics and dynamics. Postdoctoral Researcher Flavio Mercati was also honoured as one of the fourth prize recipients. All of the winning entries are available at www.fxqi.org.

Daniel Gottesman and Christopher Fuchs named APS Fellows



Faculty member Daniel Gottesman and Senior Researcher Christopher Fuchs have been elected as Fellows of the American Physical Society (APS). The Society recognized Gottesman "for his pioneering theoretical work on quantum computation and cryptography," particularly his work on quantum error correction and fault tolerance. Fuchs, whose research spans quantum foundations, quantum information, and quantum cryptography, was honoured for his "powerful theorems and lucid expositions that have expanded our understanding of quantum foundations."

First Emmy Noether Fellows announced

On March 8, 2013, International Women's Day, Perimeter announced its first two Emmy Noether Fellows: Claudia de Rham, a cosmologist at Case Western Reserve University, and Sara Pasquetti, a lecturer at the University of Surrey who works at the interface between physics and mathematics. The Fellowships, named for influential 20th century German mathematician Amalie Emmy Noether, bring exceptional early career physicists to Perimeter for periods of three months to a year.

FedDev Ontario invests in Perimeter Outreach

The Federal Economic Development Agency for Southern Ontario (FedDev Ontario) has awarded Perimeter with a $1.73 million grant to boost its educational outreach initiatives and further encourage youth to pursue studies in science, technology, engineering, and math (STEM) fields. Among other projects, Perimeter will use the grant to enhance its BrainSTEM Initiative, which involves the creation of an in-class multimedia module for grade 10 youth, teacher training on the content, and a public launch event in October 2013.

The emerging "Quantum Valley" in Waterloo Region was a major theme of the recent "Leadership Innovation Conference" held at the University of Waterloo. In the panel discussion pictured here, speakers discussed the interchange between fundamental science, strategic investment, and technological innovation. From left: Mike Lazaridis, Jon Gertner, Neil Turok, Raymond Laflamme, David Cory, and Ivan Semeniuk.

Making New Connections

(From left) Senthil Todadri, Matthew Fisher, Zhenghan Wang, and Duncan Haldane

Eight leading international scientists have been appointed to Perimeter's Distinguished Visiting Research Chairs (DVRC) program: Matthew Fisher (Kavli Institute for Theoretical Physics), Duncan Haldane (Princeton University), Theodore A. (Ted) Jacobson (University of Maryland, College Park), Peter Shor (Massachusetts Institute of Technology), Dam Thanh Son (University of Chicago), Andrew Strominger (Harvard University), Raman Sundrum (University of Maryland, College Park), and Zhenghan Wang (Microsoft Research Station Q) .

DVRCs make Perimeter their second research home, visiting the Institute for extended periods each year while retaining permanent positions at their home institutions. While here, they are full members of Perimeter's scientific community: in addition to conducting research and collaborating with colleagues, many contribute to the Institute's outreach programs, lecture in the Perimeter Scholars International master's program, and organize and attend conferences.

Since Stephen Hawking was named as the first DVRC in November 2008, Perimeter has appointed more than 35 of the world's leading physicists to the program. There are currently 33 DVRCs from across the entire spectrum of theoretical physics, appointed to three-year renewable terms.

ABOUT THE NEW DISTINGUISHED VISITING RESEARCH CHAIRS

Matthew Fisher is a condensed matter physicist at the Kavli Institute for Theoretical Physics at the University of California, Santa Barbara. His research has focused on strongly correlated systems, especially low-dimensional systems, Mott insulators, quantum magnetism, and the quantum Hall effect. Fisher received the Alan T. Waterman Award from the National Science Foundation in 1995 and the National Academy of Sciences Award for Initiatives in Research in 1997. He was elected as a Member of the American Academy of Arts and Sciences in 2003 and to the National Academy in 2012.

F. Duncan M. Haldane is the Eugene Higgins Professor of Physics at Princeton University. His research explores strongly interacting quantum many-body condensed matter systems using non-pertubative methods. In particular, his concerns include the entanglement spectrum of quantum states, topological insulators and Chern insulators, and both the geometry and model wave functions of the fractional quantum Hall effect. Haldane is a former Alfred P. Sloan Research Fellow and is currently a Fellow of the Royal Society of London, Institute of Physics (UK), American Physical Society, American Association for the Advancement of Science, and American Academy of Arts and Sciences. Haldane has been awarded the Oliver E. Buckley Condensed Matter Physics Prize of the American Physical Society (1993) and the Dirac Medal of the International Centre for Theoretical Physics (2012).

Theodore A. (Ted) Jacobson is a Professor of Physics at the University of Maryland, College Park. He is a leading researcher in the field of gravitational physics and a devoted and accomplished educator. Jacobson's research has focused on quantum gravity, testing the foundations of relativity theory, and the nature of Hawking radiation and black hole entropy. He has authored more than 100 scientific papers, which have received over 6,800 citations. He is a Fellow of both the American Physical Society and the American Association for the Advancement of Science. In addition, Jacobson has served on the editorial board of *Physical Review D* and as a Divisional Editor for *Physical Review Letters*.

Peter Shor is the Morss Professor of Applied Mathematics at MIT. In 1994, he formulated a quantum algorithm for factoring, now known as Shor's algorithm, which is exponentially faster than the best currently-known algorithm for a classical computer. He also showed that quantum error correction was possible and that one can perform fault-tolerant quantum computation on a quantum computer. Shor continues to focus his research on theoretical computer science, specifically on algorithms and quantum computing. Among his many honours, Shor has received the Nevanlinna Prize (1998), the International Quantum Communication Award (1998), the Gödel Prize of the Association of Computing Machinery (1999), and a MacArthur Foundation Fellowship (1999). He is also a member of the National Academy of Science (2002) and a Fellow of the American Academy of Arts and Sciences (2011).

Dam Thanh Son is a University Professor of Physics at the University of Chicago, a prestigious post that includes appointments at the University's interdisciplinary research institutes, the Enrico Fermi Institute and the James Franck Institute. Son is renowned for his broad research interests; he gained international prominence for his application of ideas from string theory to the physics of the quark gluon plasma. His work encompasses several areas of theoretical physics, including string theory, nuclear physics, condensed matter physics, particle physics, and atomic physics. Among his honours, Son was named an Alfred P. Sloan Foundation Fellow in 2001 and a Fellow of the American Physical Society in 2006.

Andrew Strominger is the Gwill E. York Professor of Physics at Harvard University and Director of the Center for Fundamental Laws of Nature. His research has encompassed the unification of forces and particles, the origin of the universe, and the quantum structure of black holes and event horizons, using a variety of approaches. Among Strominger's major contributions, he is the co-discoverer of Calabi-Yau compactifications and the brane solutions of string theory. With collaborators, he gave a microscopic demonstration of how black holes are able to holographically store information. Strominger's recent research has focused on universal aspects of black holes and horizons, which do not depend on detailed microphysical assumptions. His public lecture on "The Edges of the Universe: Black Holes, Horizons and Strings," is available on The Royal Society website.

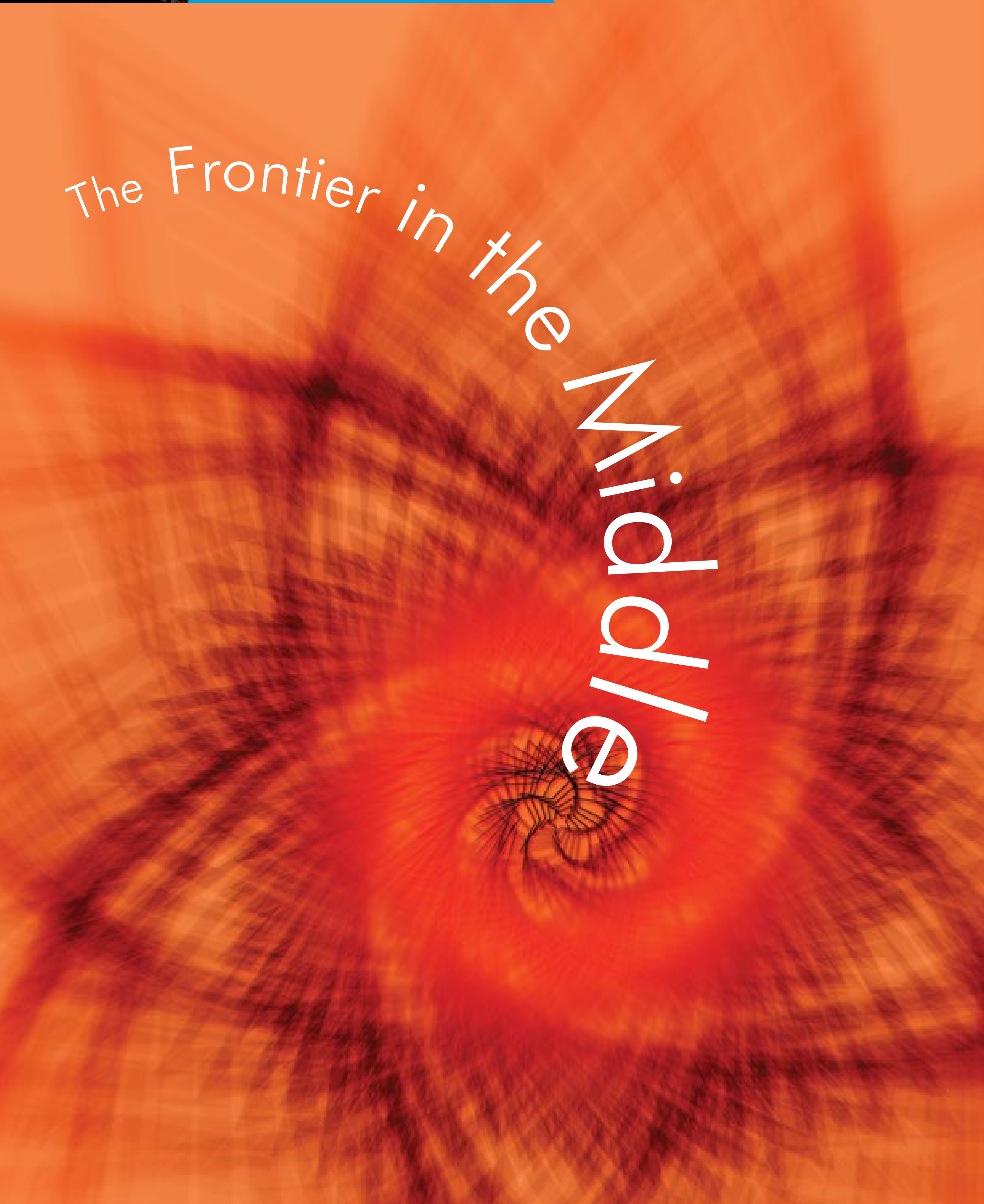
Raman Sundrum is a Distinguished University Professor at the University of Maryland, College Park, and the Director of the Maryland Center for Fundamental Physics. His research is in theoretical particle physics and focuses on theoretical mechanisms and observable implications of extra spacetime dimensions, supersymmetry, and strongly coupled dynamics. In 1999, with Lisa Randall, Sundrum proposed a class of models that imagines the real world as a higher-dimensional universe described by warped geometry, which are now known as the Randall-Sundrum models. Sundrum won a Department of Energy Outstanding Junior Investigator Award for 2001-02 and is a Fellow of both the American Physical Society (2003) and the American Association for the Advancement of Science (2011).

Zhenghan Wang is a Principal Researcher at Microsoft Research Station Q on the campus of the University of California, Santa Barbara (UCSB) and a Professor of Mathematics at UCSB on an indefinite leave. His main interests are quantum topology, mathematical models of topological phases of matter, and their application to quantum computing. Wang and his colleagues at Microsoft have been responsible for many developments, including showing that an anyonic quantum computer can perform any computation that the more traditional qubit quantum computer can. He is currently working on the theoretical foundations of the field of anyonics, broadly defined as the science and technology that cover the development, behaviour, and application of anyonic devices.

- Mike Brown

(From left) Ganapathy Baskaran and Subir Sachdev

The Frontier in the Middle



Perimeter has always defined itself by doing ambitious research in fundamental physics. We work at the frontiers, from the smallest conceivable scale – the Planck length, one-tenth to one-twentieth times the size of the proton – to the scale of the universe itself.

From the beginning, too, we've chosen our research areas strategically, looking for places which seem ripe for breakthroughs. We are interested in intersections – say, the way particle theory informs mathematics and vice versa, or the way abstruse questions about the nature of quantum mechanics lead to practical advances in quantum computation. We value work at the intersection of theory and experiment. We believe, in short, that our whole is greater than the sum of our parts.

In the last few years, Perimeter has made another strategic move, expanding our work in condensed matter physics. We started with a single faculty member, Guifre Vidal, and associate faculty member, Sung-Sik Lee, in 2011. In 2012, we were joined by three new condensed matter physicists: Dmitry Abanin, Roger Melko, and Xiao-Gang Wen, widely considered one of the world's leading theorists, who came to Perimeter from MIT as the inaugural BMO Financial Group Isaac Newton Chair in Theoretical Physics (read more about Abanin and Melko on p.16). Our postdoc and graduate student communities are likewise growing fast. In a very short time, Perimeter has become a force to watch in theoretical condensed matter physics.

How does condensed matter fit in at Perimeter? You can think of condensed matter physics as the frontier in the middle. The field typically deals with matter on what's called 'the macroscale' – the scale of pens and pencils, tabletops and chairs. The systems of interest are often exotic, but they're tangible, too: a hunk of metal, a drop of liquid. Something one can see. Compared to quasars and quantum foam, it can seem almost mundane. And yet …

In a sense, condensed matter physics is a frontier of complexity. This is the field that you would turn to in order to understand the liquid-ness of water – a single drop of which contains more than a trillion trillion molecules, each one a tiny and complex quantum mechanical system. The mathematical and physical tools needed to tackle such complexity make condensed matter one of the most challenging – and fastest advancing – physics fields around.

Condensed matter also has deep and surprising connections to other fields. For instance, consider the phases of matter. If you think of solid, liquid, and gas, think again: there are in fact more than 500 phases of matter. These phases are usually described by their symmetries. To understand symmetry, imagine flying through liquid water in an impossibly tiny ship: the atoms would swirl randomly around you in every direction. Every view, whether up, down, or sideways, would be the same. "Symmetry" is just the technical term for this sameness of some aspect of the view – and liquids are highly symmetric. Crystal ice, another phase of water, is less symmetric. If you flew through ice in the same way, you would see the straight rows of crystalline structures passing as regularly as the girders of an unfinished skyscraper. Certain angles would give you different views. Certain paths would be blocked, others wide open. Ice has many symmetries – every 'floor' and every 'room' would look the same, for instance – but physicists would say that the high symmetry of liquid water is broken.

This spontaneous symmetry breaking is commonly associated with phase transitions. You see it not only in water becoming ice at zero centigrade, but in, say, liquid helium becoming a superfluid near absolute zero. Typically, a material will exhibit some symmetry at a high temperature; that symmetry will spontaneously break and the phase will change, as the material cools. So too, the early universe, cooling after the big bang, may have undergone a sequence of symmetry-breaking phase transitions. Particle physicists and early universe cosmologists are now commonly using condensed matter tools to understand that young universe in new ways.

Moving in a different direction, some of the work of condensed matter physics has become central to the emerging fields of quantum information processing and quantum computing. The whole promise of quantum computing rests on the richness of the smallest unit of quantum information, the qubit. Unlike a classical bit, which can be only up or down, on or off, a qubit embodies a quantum mechanical property – say, the spin of an electron – and can be both on and off, both up and down, simultaneously. Where a bit can be either white or black, a qubit can be any shade of grey.

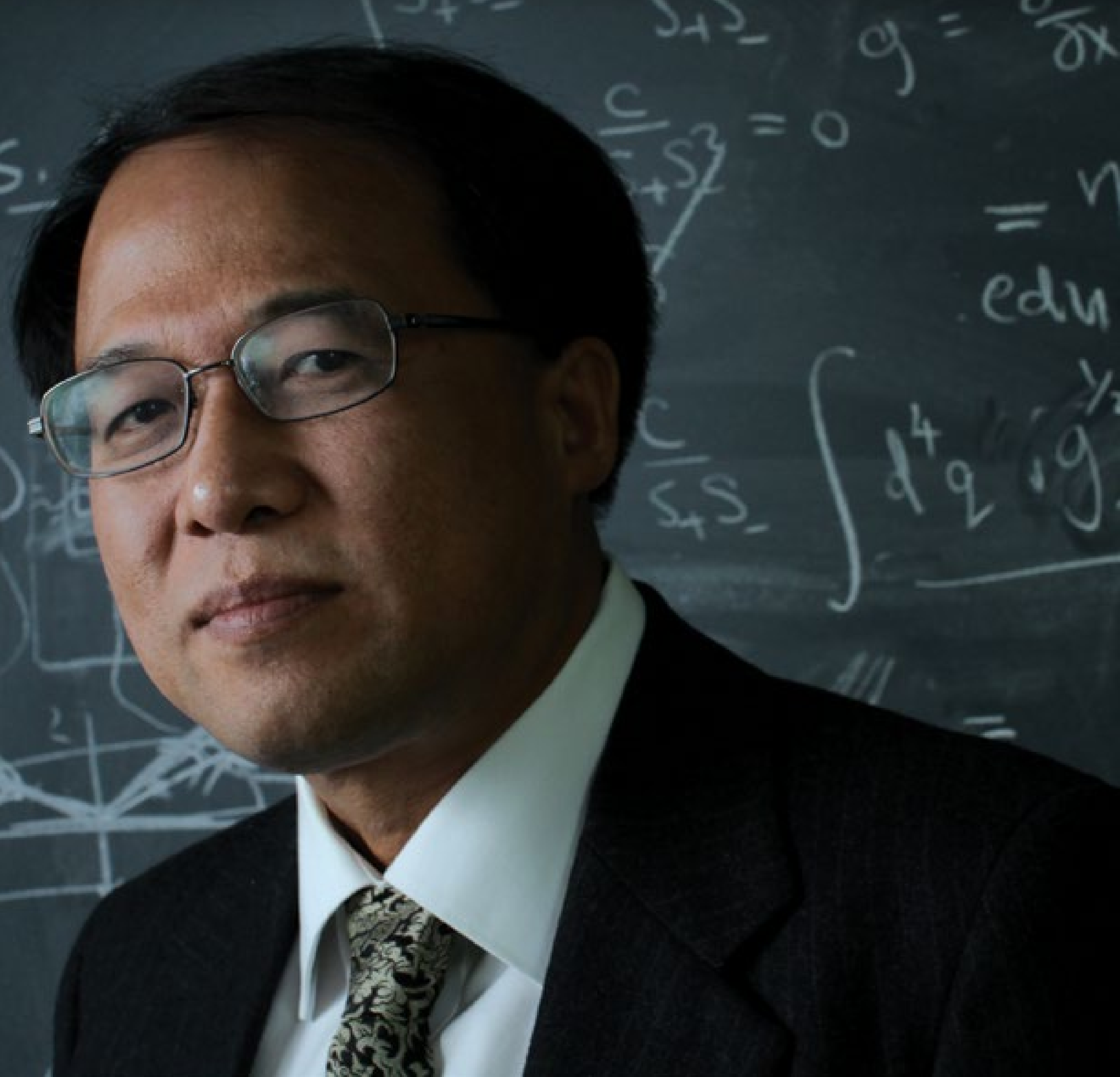
But the richness of quantum mechanical properties comes with a trade-off. Most systems that exhibit quantum effects are small, and therefore easily disturbed. It's not good to build a computer where the slightest bump can scramble your data. Condensed matter offers a way out of this dilemma. Condensed matter physicists have described and discovered systems that display quantum properties at that macroscale – materials where a quantum property does not belong to, say, a simple electron spin, but to the material as a whole. A qubit built of such a material could retain quantum richness while being workably robust. Such a material could become the silicon of the quantum computing age.

There are connections between condensed matter physics and string theory, particle physics, and mathematical physics. Ideas that have been rigorously explored in condensed matter even reach beyond physics. For instance, emergence – the principle that the properties of a system can be quite different from the properties of its component parts – is a hot topic in biology, neurology, and even urban planning. There are physicists who think that the laws of the universe may be emergent and that emergence explains their beauty.

Don't let the sound of 'tabletop scale' fool you – condensed matter physics is an exciting new frontier.

- Erin Bow

Beauty from the Mess: A Condensed Matter Model for the Universe



Throughout history, people have attempted to understand the universe by dividing matter into smaller and smaller pieces. This approach has proven extremely fruitful: successively smaller distance scales have revealed successively simpler and more fundamental structures. At the turn of the last century, chemists discovered that all matter was formed out of a few dozen different kinds of particles – atoms. Later, it was realized that atoms themselves were composed out of even smaller particles – electrons, protons, and neutrons. Today, the most fundamental particles known are photons, electrons, quarks, and a few other particles. Given their history, it's natural to wonder if photons, electrons, and quarks are truly elementary, or if they are instead composed of even smaller objects. A great deal of research has been devoted to answering that question. But it may be that the question itself is flawed.

The process of searching for what's "truly elementary" is called the reductionist approach. Reductionism is based on the assumption, usually unspoken, that we can understand the nature of the universe by understanding its smallest pieces and the rules that govern them. There are many examples from condensed matter physics indicating that the reductionist approach can lead us astray. For example, we know that a sound wave can propagate inside a crystal. According to quantum theory, the vibrations of the waves are quantized, which make these waves behave like particles, called phonons. Phonons are no less particle-like than photons, but no one attempts to gain a deeper understanding of phonons by dividing them into smaller pieces. This is because phonons – as sound waves – are collective motions of the atoms that form the crystal. When we examine phonons at short distances, we do not find small pieces that make up a phonon. We simply see the atoms in the crystal.

The idea of phonons suggests an alternative to the reductionist approach. Are electrons, photons, and other elementary particles collective modes of some deeper structure? If so, what is this "deeper structure"? In other words, is it possible to construct a condensed matter model of the universe?

What would a condensed matter model of the universe look like? Well, the laws of physics seem to be composed out of five fundamental ingredients. (For completists, these five ingredients are identical particles, gauge interactions, Fermi statistics, chiral fermions, and gravity.) Our ambition would be to find a "deeper structure" that gives rise to all five of these phenomena. In addition to being consistent with our current understanding of the universe, such a structure would be quite appealing from a theoretical point of view: it would unify these mysterious phenomena based on a single simple origin. This was thought to be impossible since those phenomena are so different and seem totally disconnected.

This would be a major step forward. The Standard Model of particle physics leaves one ingredient out entirely – gravity – while describing the other four in a single theory. That perhaps looks like a near success, but unfortunately, each of these "ingredients" was introduced into the theory independently and by hand. (For example, field theory was introduced to explain identical particles; vector gauge fields were introduced to describe gauge interactions; and anticommuting fields were introduced to explain Fermi statistics.) One wonders: where do these ad-hoc explanations – these mysterious gauge symmetries and anticommuting fields – come from? Why does nature choose such peculiar things as fermions and gauge bosons to describe itself? We might hope that the "deeper structure" that we are looking for can resolve these mysteries.

For my own part, I advocate for an entirely different view of elementary particles based on the principle of emergence. Emergent phenomena are those that, like phonons, arise as collective modes of a material. What material? Well, hidden in the reductionist approach is the assumption that the vacuum is merely empty space, just an arena in which we place particles and divide them. In the emergent approach, we instead treat empty space as a dynamical medium formed by qubits – qubits being the simplest and most fundamental object in quantum theory. My colleague, Michael Levin, and I have studied a system of qubits which organize into strings. As the qubits fluctuate, the strings weave and wave around and form an interesting quantum material: we call it a string-net.

Could string-nets of qubits be the "deeper structure" behind the mysteries of the universe? Well, perhaps. Our calculations show that collective waves of string-nets are gauge bosons (such as the photons that make up light), while ends of strings are fermions (such as electrons). What's more, the string-net model reproduces the known laws of electromagnetism and strong/weak interactions. In short, string-nets produce (as emergent properties) matter, forces, and the rules that govern them. All those can arise from a single origin: qubits.

This is not a complete model. The emergence of gravity and chiral fermions remain open problems, though much progress has been made recently, which makes me hopeful. But though the model is incomplete, it hints at a new view of some of the fundamental and mysterious properties of nature. Perhaps instead of trying to break messy complex structures into simple and beautiful building blocks, we should consider the possibility that nature works the other way around. What if elementary particles are not elementary, but emerge from the collective motions of a dynamical medium – the vacuum? What if physical laws are emergent, too? The fluctuation of string-nets formed by qubits can be quite arbitrary and ugly. But, in this view of nature, beauty emerges from the mess.

- Xiao-Gang Wen

Xiao-Gang Wen is the BMO Financial Group Isaac Newton Chair in Theoretical Physics at Perimeter Institute.

Quantum Spin Liquids

A Chat with Steven White

Photo Credit: Steve Zylius/UC Irvine Communications

Professor Steven White, who hails from the University of California at Irvine, is one of Perimeter's Distinguished Visiting Research Chairs, eminent scientists who visit Perimeter regularly and make the Institute their second research home. During his March 2013 visit, he sat down with Inside the Perimeter *to talk about his recent work successfully modelling a quantum spin liquid, which was featured on the cover of* Science *magazine.*

Inside the Perimeter: Let's start at the beginning. What *is* a quantum spin liquid?

Steven: One of the fascinating things about quantum mechanics is that more than one thing can happen at the same time. Normally, that's hidden from us, so you see a classical world where – for example – this chair is definitely *here*, and not someplace else at the same time.

But the quantum world is different. Something small – an electron, say – might be in many places at once and you can't pin it down. We're almost used to that, but it's still very interesting when that sort of thing happens on a bigger scale than just one atom.

So a quantum spin liquid is one of those places. To make one, you need several things. You have to start with something that has a little magnetic moment on each atom, so that each atom acts like a tiny magnet. This little magnet has a north and a south pole, and it has to point in one direction or the other. But with quantum mechanics, we can also have that spin pointing simultaneously both up and down. And that's what happens in a quantum spin liquid: all its magnet moments are pointing simultaneously in different directions.

Inside: How's that different from an ordinary magnet?

Steven: If you have an ordinary magnet which is very hot, then all the little moments probably point in all sorts of different directions. But that's just because the thermal motion is moving them around. You can still think of each one as pointing in a definite direction.

Inside: And then you cool it.

Steven: Right. And ordinarily, as the thermal motion becomes less, all the magnetic moments will align and you'll get a ferromagnet. You see a big magnetic effect because all the little magnets are pointing together. The other thing that is even more common, microscopically, but harder to see, is that the magnetic moments will align opposite to each other – that's called an antiferromagnet.

But either way, the little magnetic moments – the spins, which are the same thing – are locking into a structure. If you could somehow look at the crystal lattice, you'd see this one pointing up, and the next one pointing down, in a very ordered, predictable way.

Inside: In other words, the spins would freeze into place.

Steven: Yes. And that makes intuitive sense, right? Everything freezes – by which I mean becomes more ordered – as the temperature approaches absolute zero.

But a quantum spin liquid is different. Even as you cool it toward absolute zero, so that none of the motion is from temperature, the spins still move around – you can think of them as moving around due to quantum fluctuations. Each magnetic moment is simultaneously in many different positions at once.

Inside: Is that why it's called a spin *liquid*?

Steven: Right, because it didn't freeze. The spins are like the atoms in a liquid dancing around.

We've known for years that a spin liquid was a theoretical possibility, but it's been amazingly difficult to find a real example. In the last few years, we think we've found some, most famously herbertsmithite, where we can see experimentally that this kind of behaviour takes place. But there's been a piece missing on the theoretical side, too. We needed to write down the basic equations that describe the quantum mechanical systems, and to solve them and find a quantum spin liquid as a result.

Inside: And that's what you've just done – the work that landed you the cover of *Science*.

Steven: Yes. Now, it's often possible to cook up a model that gives a particular answer. What's difficult is to start with a realistic, unbiased model that doesn't have quantum spin liquids as a forced ingredient, and then solve that. That's what we did. We took a realistic model and used a mathematical technique called the density matrix renormalization group (DMRG) to solve it on the computer. We found that the model's solution – its ground state – was a spin liquid.

Inside: Is this where we have to start talking about materials that exhibit quantum mechanical properties at macroscales?

Steven: Exactly. This is where things are quantum, not just one atom at a time, but on the scale of rocks and chairs.

Remember when I said that what was special about a quantum spin liquid is that it doesn't order – doesn't freeze – even at absolute zero? It turns out that there is a more subtle thing going on. There's a hidden kind of order, called topological order, which [Perimeter Faculty member] Xiao-Gang Wen essentially invented.

Topological order is now a key idea for understanding quantum spin liquids. There are different types of topological order and so when we find a spin liquid, we'd like to understand what type of topological order it has.

This is important because some of the types of order are stranger – more quantum – than others. If you could find the right kind of topologically ordered material, and work with it, engineer it, it might be the right thing with which to build a quantum computer.

Inside: I think I understand that that's because the information would be more durable, because it's encoded in many particles at once, and not in, say, a single electron spin …?

Steven: That's right. The information resists decoherence because it's encoded in the bulk at large distances. We don't think the particular quantum spin liquid we've described has this most interesting kind of topological order, but obviously we're just getting started.

Inside: There are a lot of interesting overlaps between condensed matter physics and quantum computing these days.

Steven: And they go in both directions. The people trying to figure out how to program a hypothetical quantum computer have developed some novel ways of thinking about quantum mechanical systems. Some of those ideas tell us something new about solving those systems even if you don't have a quantum computer, even if you just have a regular computer.

[Perimeter Faculty member] Guifre Vidal was really the first person to make this connection from quantum information to solving quantum mechanical systems in condensed matter and bring the ideas across in a big way. Before that, the two fields had not known so much about each other.

Inside: But now –

Steven: Let me put it this way. In 1992, I invented DMRG, which has become a very popular way to solve quantum mechanical systems in condensed matter. In inventing DMRG, I thought about lots of different things. Many people improved DMRG, but most of the developments were not a surprise to me, because I'd put in so much thought. Everything just seemed to fit.

But then the new ideas of quantum information came along – and all of a sudden I was getting surprised quite often. And that has been really quite wonderful, to have completely new, unanticipated connections that came in. There were new ways of thinking about things – there were problems I had been stuck on and there were suddenly solutions in completely new directions. It's been wonderful fun.

- Erin Bow

Mysteries at the Tip of a Pencil

Dmitry Abanin, new to Perimeter's growing condensed matter effort, is interested in understanding quantum effects in relatively macroscopic systems – systems with a large number of particles – and in highly excited states. Abanin recently joined Perimeter's faculty, following postdoctoral fellowships at Harvard and the Princeton Center for Theoretical Science. He received his PhD from MIT in 2008.

"Usually, you think of quantum phenomena as something inherent to very small objects, like atoms. But it turns out that particles can organize into collective states, and then quantum effects become visible in measurable macroscopic physical quantities, like conductivity. For example, one material where collective quantum effects are especially rich, and I've done a lot of work on, is called graphene."

Graphene was discovered in 2004 and it is a truly two-dimensional material. It is a thin film of carbon atoms arranged in a honeycomb pattern, just one atom thick. It has excited the world of condensed matter physics with its unusual properties and potential for practical applications. "Electrons in graphene behave like quasi-relativistic particles, so you find that these electrons are behaving more like neutrinos than normal electrons," says Abanin. "The optics, the electrical and thermal conductivities, these are all very unusual. What's most interesting to me as a theorist are the quantum Hall effects. You find that certain components of the conductivity of the material are quantized, only in terms of fundamental physical constants (like the Planck constant and electron charge). That may sound confusing, but here's what's remarkable about it: despite all the disorder in the material, despite the imperfections, its conductivity depends only on the fundamental physical constants. This is not something we usually see in nature."

The possible applications of such macroscopic materials exhibiting quantum properties are very exciting for condensed matter physicists. Abanin's work with graphene is only part of what he does, but it's a sentimental favourite – in part because it's literally with him every day. "Graphite – the stuff at the end of your pencil – is made from weakly-coupled layers of graphene," he points out. "When you write with a pencil, you are peeling off layers of graphene and leaving them on the page. With some work, you could get the layer on the page down to a single atom thick, and that material on your page would be exhibiting all of these exotic quantum effects in ways you can't see with your eye."

Quantum effects at the end of your pencil – that's pure condensed matter physics.

- Phil Froklage

Quantum Physics You Can Use

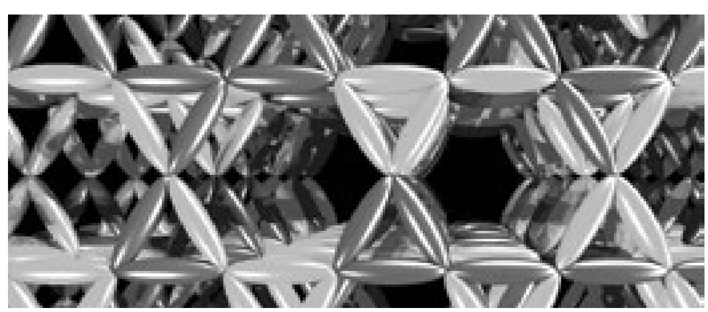
Roger Melko describes himself as a "blue collar" physicist: "I'm just working at this for a living, and physics seemed to me the best way to contribute to the world and to the advancement of science."

Melko does foundational quantum many-body theory motivated by condensed matter physics. He focuses on how quantum theory works with matter: using large-scale computer simulations, he mathematically models materials that don't exist in nature but tell us a great deal about macroscopic manifestations of quantum physics.

"I'm a theorist, but in my own way I'm trying to run experiments. Say an experimentalist wants to understand a certain kind of crystal. They will walk over to their crystal growth facility, chip one off, and study it. I'm trying to study crystals we don't find in nature – predicting future materials we may be able to manufacture one day, that have interesting quantum properties."

Melko offers superfluids as an example: "If you cool helium to two degrees Kelvin, it exhibits a single, beautiful quantum wave function. The question then is how to use it – what would a macroscopic, quantum material look like if you could hold it in your hands? This is why I call myself a blue collar physicist: I'm looking for quantum physics you can really use. Condensed matter is going to be the field that defines new technologies. It's more than just pushing the boundaries of academic knowledge; I truly believe that our field will define the future of the human race."

- Phil Froklage



Representation of a layered 'kagome' lattice

"Sum the Feynman diagrams."

What the helicity? Though our quantum field theory lectures left dawdlers in the dust, I laid down my pencil. I had never studied QFT. I had never drawn Feynman diagrams. I thought that diagrams were not the sort of things that summed; numbers were.

Thanks to my literary background, I was taking physics too literally. It was slowing me down.

As an undergraduate, I'd analyzed Aristotle's *Ethics* while my future PSI classmates had transformed tensors. As they'd studied combinatorics, I'd read Kant. I'd concocted a physics-centric major at my liberal arts college – from physics courses, math, philosophy, and history – but my education included more breadth than bosons. When I arrived at PSI, I felt out of place. Over lunch, my classmates talk about wedge products; the only wedge I felt qualified to discuss was the cheese in my salad. Downing the cheese, I tamped down on my literary leanings. But they seeped, like acid from a lemon, over my autumn.

I felt behind. During weekends, I haunted the fishbowl, the glass-enclosed reading room in Perimeter's library. Commandeering half a wooden table, I stacked textbooks on my right and scratchwork on my left. Then something unexpected hooked me.

"[L]ike Aesop's fables," Steven Weinberg had written in *Gravitation and Cosmology*, "[the Schwarzschild Singularity] is useful because it points to a moral, that what appears in one coordinate system to be a singularity may in another coordinate system have quite a different interpretation." What a striking simile, I thought.

After hesitating, I slipped a notebook from my backpack. I scribbled Weinberg's sentence, then shoved the notebook into its pocket. For old times' sake, I thought. For the time when I had time for words. Zipping the pocket closed, I slid my calculus closer.

The notebook emerged the following week, when I caught a pun during a lecture. Between solving tutorials, I recorded personification. ("The annihilation operator eats the particle," a student explained. "Bon appétit," I thought.) The farther lectures strayed into abstraction, the faster the notebook filled. Recording figures of speech cut into my work time, but I couldn't help myself.

Thank goodness. Recognizing poetry saved my science.

I came to understand Feynman diagram language as metalepsis – a layering of metaphor atop metaphor that shortens the path for thought. Discovering how the diagrams work – that I had depicted muon decay correctly, that I had calculated a decay rate correctly! – lit me up like photon production. Instead of impeding, my literary training clarified physics.

The liberal arts illuminate what we mean and – that object of science – the world as it is. I want to see the world as it is: to puzzle over diagrams, to haunt the library, to further quantum information. But my lens on the world differs from the typical scientist's.

What appears in one coordinate system to be physics may in another coordinate system be poetry.

- Nicole Yunger-Halpern

Nicole Yunger-Halpern is a student in the Perimeter Scholars International program.

World's First Glimpse of Black Hole 'Launchpad'

A strange thing about black holes: they shine.

Many galaxies, including our own Milky Way, have a huge black hole lurking at their cores. In about 10 percent of such galaxies, the hole gives off huge, tight streams of electrons and other sub-atomic particles travelling at nearly the speed of light. These powerful jets can extend for hundreds of thousands of light years. They can be so bright that they outshine the rest of the galaxy combined.

Work being done by a team that includes Perimeter Associate Faculty member Avery Broderick may shed light on the origin of these bright jets. By combining and comparing data from three radio telescopes, they are beginning to image the base of a black hole jet – its 'launchpad' – for the first time.

The team, coordinated by Shep Doeleman at MIT's Haystack Observatory, used the Event Horizon telescope, which is actually a network of three radio telescopes spread out over the Earth. The subject of their study is M87, a giant elliptical galaxy just over 50 million light years from our own. That is close as galaxies go, but a long way away considering that the horizon of the black hole the team imaged is about the same size as a single solar system. It is as if the telescope could make out a poppy seed from across a continent or spot a softball on the moon. "These are some of the highest resolutions ever accessed in the history of science," says Broderick.

Broderick sums up the problem the team tackled: "With black holes, stuff is supposed to go in, and yet here we see all this stuff coming out with huge energies. Where does that energy come from?"

There are two possibilities. The first is that a black hole itself is a great reservoir of energy – a spinning black hole has a huge amount of rotational energy that the jets might tap. The second possibility is that the energy might come from some accretion process – the accretion disk is the dusty spiral of stuff falling into the black hole. The physics of accretion are not yet well understood.

With the new data coming in from M87, theorists like Broderick can start to tell the difference between these models of hole-driven jets and accretion-driven jets. The image is not yet sharp – it is trickling in pixel by pixel – but that, says Broderick, "is enough to tell the difference between your mother and your daughter." With images like the one the team is working on, we can begin to narrow in on the origin of ultrarelativistic jets.

"The first thing we learned is that the launching region is quite small," says Broderick. The jets are coming from quite close to the black hole's event horizon: the point of no return where even the light from objects tumbling into the black hole is lost. While this is not quite enough to rule out the idea that jets might be powered by accretion physics, it is clear that energy is coming either from the black hole or from the accretion processes happening right next to the black hole.

"We are now beginning to see that spin is playing a role in jet production," says Broderick. "That is, not only can we say that the jets originate near the black hole, but because the emission region is so small, it must be coming from a rotating black hole."

"The black hole is really the engine that drives the jet," he adds. "It's an extraordinary thing."

- Erin Bow

The Birth Cry of a Black Hole

Might we someday predict – and then carefully observe – the birth of a black hole? Perimeter Faculty member Luis Lehner thinks it's possible.

Lehner and his collaborators have been studying the mergers in compact binaries – that is, binary 'star' systems where both stars are extraordinarily dense: either neutron stars or black holes. Lehner studied two kinds of mergers: one in which a neutron star orbiting a black hole gets destroyed and sucked in, and a second in which two neutron stars spiral together and collide, forming first a hypermassive neutron star and then collapsing to form a new black hole. Either event is fantastically powerful.

Neutron stars pack the mass of the sun into a sphere smaller than most cities. Conjure the familiar image of spacetime as a rubber sheet with the sun dimpling it like a bowling ball. A neutron star dimples the sheet like a pinhead that weighs as much as a bowling ball. Thus, a neutron star 'dimple' is more like a well: steep-sided and deep. A black hole, to go one step further, is like a bottomless pit. The energy packed into either distortion of spacetime is tremendous, and when two such distortions merge, they set off ripples in the rubber sheet – gravitational waves.

Gravitational waves have long been predicted by Einstein's theory of general relativity, but they have never been observed. That may soon change – the first of a new generation of gravitational wave detectors came online in 2002 and more are being built and improved every year. Massive binary mergers, of the kind Lehner has been modelling, are thought to be the ideal source for the signal these detectors are working to capture.

They are also thought to be the source of gamma ray bursts: intense bursts of high frequency light that have been spotted all over the sky for 25 years. Short gamma ray bursts last less than two seconds – but in those two seconds, they outshine the rest of the universe combined. These bursts are thought to be powered by the way the two stars twist and tangle their magnetic fields as they spiral in, eventually creating fields trillions of times stronger than the Earth's magnetic field.

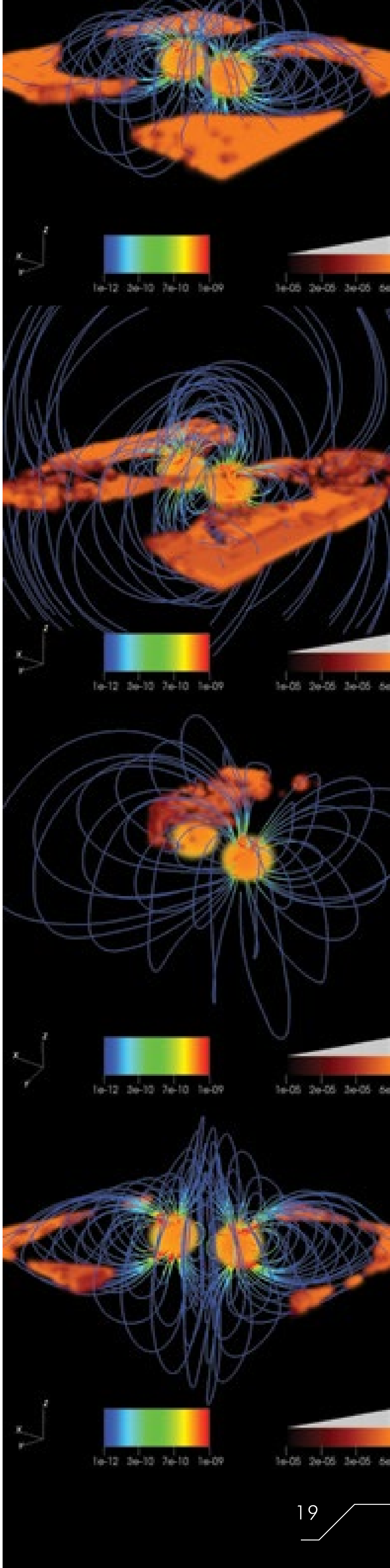
What Lehner and his colleagues have done is shown how the two signals – the gravitational wave and the electromagnetic radiation from the system – might be related. Their new model examines the magnetic fields both inside and outside the colliding stars – an improvement on previous models whose simplifications made them unable to cope with both the inside and outside regions simultaneously.

The new model predicts that there should be a strong electromagnetic counterpart to the gravitational wave signal the neutron star merger puts out. Having two signals – one gravitational and one electromagnetic – gives scientists two ways to observe the same event. That's a new and hot idea in the field that goes by the name 'multimessenger astronomy.' Lehner's work will be key as scientists work to understand to what extent multimessenger astronomy is possible.

The promise of multimessenger astronomy is more than just two sets of data. It allows one model to check the other. It allows us to look at different parts of the system – at gravitational waves from deep within the merging stars and electromagnetic signals from their surface, for instance. And – because gravitational waves ramp up slowly before neutron star mergers – they could give us warning that a neutron star merger is about to happen, allowing us to turn our telescopes and catch the gamma ray burst: the birth cry of a black hole.

- Erin Bow

Artist's conception of a black hole jet. Credit: Chris Fach.



Magnetic field configurations (blue lines) and current sheets (orange lines) for several different configurations of merging neutron stars.

EQUINOX SUMMIT: LEARNING 2030 reimagines a school for the future

Photo Credit: Jonathan Baltrusaitis

How can we equip today's learners to succeed in tomorrow's world?

From September 29 to October 3, pioneering experts, young innovators, and experienced advisors from around the world will gather together at Perimeter Institute to rethink the ideal learning environment for high school students.

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- Graham Brown-Martin, thought leader and Founder of Learning Without Frontiers
- Jennifer Groff, Co-Founder, Center for Curriculum Redesign
- John Kershaw, President of C21 Canada
- Greg Butler, Director of Education Strategy, Microsoft Corporation
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Quantum Mechanics Comes On-Shell

Using complex momenta to simplify calculations and open doors to new physics

Is this the new face of Feynman diagrams?

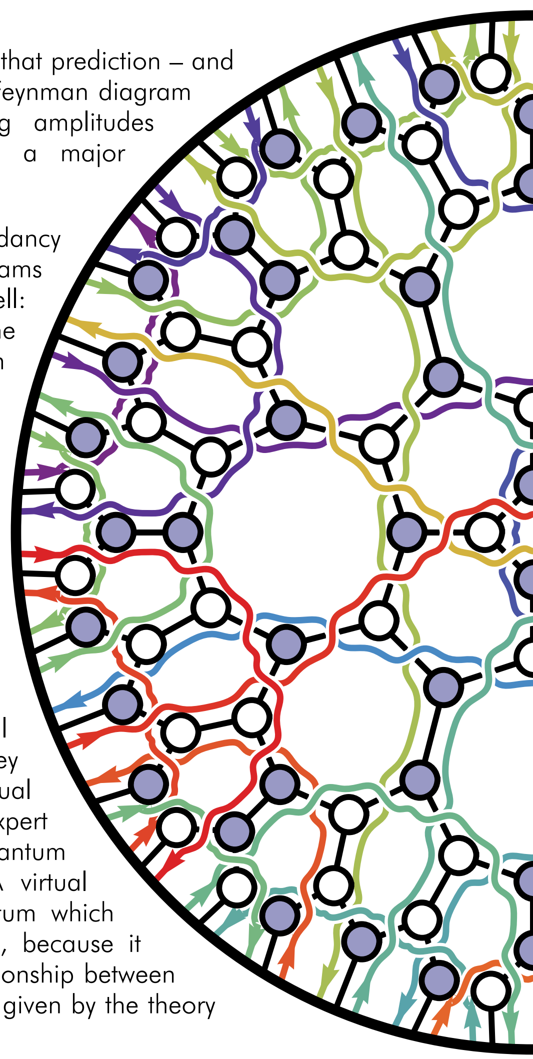
"Well," says Perimeter Faculty member Freddy Cachazo, modestly, "that's a provocative question. Ask people again in 65 years."

It was 65 years ago that Richard Feynman introduced his diagrams to the world, simplifying the way physicists model particle interactions. Generations of researchers since then have used Feynman diagrams to help them calculate what happens when two or more particles collide, a process generally known as scattering. Visual and simple, Feynman diagrams have become the standard way to get an intuitive handle on what would otherwise be a rather abstruse calculation.

"Feynman diagrams were and are a dream come true," says Cachazo. "They work very well; they have allowed us to test the predictions of quantum field theory to incredible accuracy. Also, they make locality, one of the two pillars of quantum field theory, manifest along the computation. But all this comes at a cost: Feynman diagrams contain a large amount of redundancy." Diagram by diagram, Feynman diagrams can produce as final states particles that are physically impossible. You have to add up all the possible diagrams to show that the probability for physically impossible states is zero.

The trouble is "all possible diagrams" can be many, many diagrams. Calculating what happens when massless particles such as gluons collide, for example, requires hundreds of Feynman diagrams even in simple events when just two gluons interact to produce a few more. Each of these hundreds of diagrams produces many terms in the formula; this makes it infeasible to do these calculations by hand. These problems can now be handled using powerful computers – but complex collisions, like the ones happening at the LHC at CERN, are beyond the reach of the best supercomputers.

A more efficient process for calculating scattering amplitudes is at the top of every particle physicist's wish list. At CERN and elsewhere, researchers smash together sub-atomic particles at high energy, looking for new particles and forces not accounted for in the Standard Model of physics. In order to discover new phenomena, though, it is necessary to first precisely calculate what current theoretical models predict about particle interactions at very high energies – you can't spot the unusual unless you know exactly what the usual looks like. Calculating scattering amplitudes is central to that prediction – and the redundancy in the Feynman diagram approach to scattering amplitudes has, until now, been a major stumbling block.



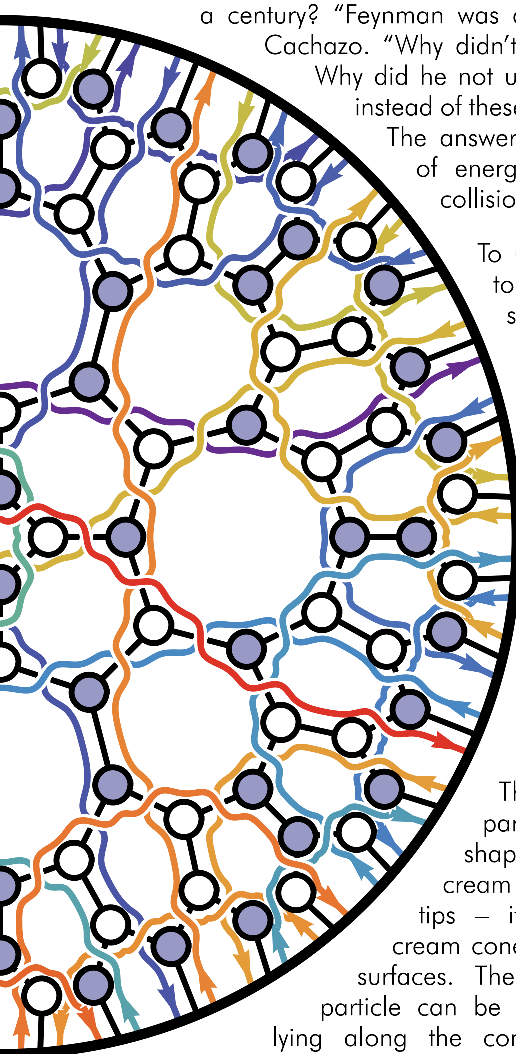
Where does the redundancy in Feynman diagrams come from? In a nutshell: virtual particles. Anyone looking at a Feynman diagram might well get the impression that the diagram is telling a story of particles interacting. But the internal lines in Feynman diagrams – the ones tracing 'particles' that are neither input nor output – do not actually represent physical particles. Instead, they are said to represent virtual particles – what an expert might call 'generic quantum field configurations.' A virtual particle has a momentum which is physically impossible, because it does not obey the relationship between energy and momentum given by the theory of relativity.

"It is natural to ask if virtual particles are strictly necessary," says Cachazo. "Is it possible to describe the interaction of physical particles using only physical particles? The new answer is yes."

Cachazo is part of a small group of mathematical physicists who have developed a new scheme to do just that. The others are Nima Arkani-Hamed of the Institute for Advanced Study (who is also a Perimeter Distinguished Visiting Research Chair), Jacob Bourjaily of Harvard, Alexander Goncharov of Yale, Alexander Postnikov of MIT, and Jaroslav Trnka of Princeton. In a massive, 152-page paper entitled "Scattering Amplitudes and the Positive Grassmannian,"(arXiv:1212.5605) the team walks the physics community through the elegant mathematical ideas behind a new system for calculating what happens when particles interact. In this new picture, virtual particles make no appearance at all.

With virtual particles eliminated, calculating scattering amplitudes becomes astonishingly simple. The paper is the culmination of over a decade of work, and it's likely to have wide implications for physics and mathematics. To begin with, this system may well revolutionize the way particle physicists do their most essential calculations.

But let us back up a bit. If getting rid of virtual particles is a good idea, then why has the picture featuring virtual particles guided calculation of particle interactions for nearly three-quarters of a century? "Feynman was a genius, after all," says Cachazo. "Why didn't he use Occam's razor? Why did he not use only physical particles instead of these strange virtual particles? The answer is that the conservation of energy and momentum in a collision makes it impossible."



To understand this, we have to understand the mass shell.

In modern physics parlance, particles are said to be "on the mass shell" or simply "on-shell," if they satisfy the known relationship between energy and momentum given by Einstein in his theory of special relativity. Virtual particles are those that don't satisfy this relationship.

The mass shell for massless particles like photons is shaped like two empty ice cream cones, joined by their tips – if you can imagine ice cream cones with three-dimensional surfaces. The momentum of a real particle can be represented by a vector lying along the cones' 'surface.' It's high school physics that when two particles collide, their total momentum has to be preserved: the two momentum vectors should be added. And here's the catch. Pretend that two massless on-shell particles interact and produce a third particle. The momentum vector of the final particle won't lie along the surface of the cones, unless the original momenta are parallel. These particles that don't lie on the surface are said to be "off the mass shell" or "off-shell."

That's where Feynman's virtual particles come in – to account for these off-shell particles.

What the researchers have proposed instead is that the mass shell be represented more generally, in a complex space. (In other words, they consider that the momentum of each particle can have real and imaginary components.) You can then add the complex vectors and the resultant vector will stay on-shell. The external particles must still be real; the internal particles – which in Feynman's approach were off-shell – are now on-shell, but with complex momentum.

"People have always said that quantum mechanics has to do with off-shell particles running in loops," says Cachazo. "You're allowed to be a little bit off-shell if it's for a small amount of time, because of the uncertainty principle. What we have shown in several theories is that all of quantum mechanics can be reformulated purely on-shell. There is no need to go off-shell anywhere."

Why does using complex numbers yield such simple calculational forms for the scattering amplitudes? That's not yet clear, but it appears to point to fundamental, as-yet-undiscovered physics related to theories of space and time.

With all the redundancies of Feynman diagrams stripped away, amazing physical and mathematical structures that were hidden within quantum field theory are laid bare. "One of the most surprising new connections to mathematics is to the concept of total positivity in combinatorics," says Cachazo. "Very roughly, this is a generalization of the way convex polytopes are defined and hints at the possibility that scattering amplitudes are volumes of certain polytopes. This geometrical picture gives new insights into locality – and unitarity – as derived geometric concepts."

If we are lucky, this new mathematical lens on scattering theory may bring new ideas to light.

Expect this major paper to be a focal point for years to come.

- Erin Bow

On-shell diagrams, like the one pictured here, are a new visual system for guiding and structuring the calculations of what happens when particles interact. They eliminate the redundancy introduced by Feynman diagrams and make calculating scattering amplitudes astonishingly simple.

The Sophistication of Symmetry

Conference participants at "New Mathematical Structures in Supersymmetric Gauge Theory"

Symmetry is a concept dear to physicists. They talk about global symmetries, local symmetries, broken symmetries, accidental symmetries, and others. One reason for this is that nature itself operates in a highly symmetric fashion; symmetries are prevalent in relativity, electromagnetism, particle physics, and so on. Another reason for thinking about symmetry is that it is a powerful tool for solving problems. How fortunate!

To see symmetry in action, consider a sphere. Since a sphere looks the same no matter which way it is rotated, it is said to be highly symmetric. Once a physicist recognizes this symmetry, it greatly simplifies problems involving spheres, since it can be concluded that the orientation of a sphere will have no bearing on its physics. Contrast this with a plum, whose lack of symmetry makes it a difficult object to deal with.

A sphere is a rather simplified example, but the organizational power of symmetries can be used in more sophisticated settings, like in quantum field theory, which underlies the Standard Model of particle physics and describes many condensed matter systems. Although ubiquitous, quantum field theories are generically quite difficult to solve exactly, and practitioners are usually satisfied with approximate results. However, the abundance of symmetry in some theories allows physicists to obtain exact results and to identify their connections with other theories. Researchers at Perimeter and elsewhere have made a number of very exciting recent discoveries in this vein, and it was these tantalizing new results that brought mathematicians and physicists to Waterloo for the "New Mathematical Structures in Supersymmetric Gauge Theory" workshop in March.

As the title of the workshop suggests, the theories that have generated excitement are so-called supersymmetric gauge theories. Supersymmetry is often presented as a popular physics model in which every known fundamental particle is granted a superpartner, which we might one day discover experimentally. Doing so would help explain the otherwise perplexing properties of fundamental particles, such as the curiously light mass of the newly-discovered Higgs boson. But there is more to supersymmetry than a doubling of particles. Supersymmetry is also a symmetry, as you have probably guessed, and thereby provides theorists with a new handle on quantum field theories. So, while we have yet to discover any superparticles experimentally, supersymmetry is thriving as a 'theoretical laboratory' in which to investigate quantum field theory and its connections to mathematics.

For instance, many of these theories are dual to other theories. That is, calculating a quantity in one theory gives you the answer for a different quantity, in a different theory, for free. So when new results are obtained in one theory, they can be checked against physicists' expectations from their understanding of the dual theory. Getting the same answer in two different ways is a strong sign that a result is correct. However, in some cases, the quantity a physicist calculates in one theory is dual to some poorly understood mathematical object, so new math is required and simultaneously hinted at. This gets the mathematicians and physicists talking. "As an example," explains Jaume Gomis, Perimeter Faculty member and one of the conference organizers, "it was discussed how these physics-based methods have been used to obtain the first new topological invariants (Gromov-Witten invariants) in 15 years, and that mathematical methods to reproduce these are currently out of reach."

Knowing that the cutting edge of physics runs in tandem with the forefront of mathematics, Gomis and co-organizer Davide Gaiotto, another Perimeter Faculty member, set up the meeting to bolster communication between the two fields. To achieve this goal, the three-day workshop was intentionally kept small; only a dozen or so researchers and a handful of students were invited to attend. The speakers were given ample time to explain the details of their work on the blackboards of the Sky Room and equal time was dedicated to discussion, though Gaiotto admits that most speakers had so much to say that they continued speaking for the entire discussion period. It is a good sign for the field that researchers have more results than time to explain them!

The intimate workshop proved to be ideal for connecting mathematicians and physicists. Says Gaiotto, "I have especially enjoyed learning what the mathematicians at the workshop have been thinking about recently. As the timescale for math papers is somewhat longer than for physics papers and reading a math paper can be challenging for a physicist, it is useful to hear directly about it in a workshop explicitly devoted to fostering communication." With the lines of communication now successfully opened, we can look forward to new advances in math and physics that should help us understand our own highly symmetric world.

- Ross Diener

Ross Diener is a PhD student at Perimeter and McMaster University.

(From left) Davide Gaiotto and Maxim Kontsevich

Experimental Search for Quantum Gravity: The Hard Facts

October 22-25, 2012 I Watch the talks! pirsa.org/C12043

Quantum gravity tries to unify quantum field theory with general relativity by exploring what it may mean for spacetime to be quantized. Several different approaches, based on different principles and assumptions, are currently developing in parallel. The first experimental results which may help us distinguish between these approaches to quantum gravity are just becoming available. This forward-looking workshop brought together the top theorists and experimentalists, representing a variety of approaches to quantum gravity. The discussion ranged widely, including particle physics, astrophysics, cosmology, and high precision measurements. The aim of the workshop was to assess the status of different proposals for quantum gravity phenomenology in the light of recent experimental results, and to discuss and stimulate the new ideas and proposals that will shape the future of this rapidly changing field.

Applications of Jet Substructure to New Physics Searches

February 21-23, 2013 I Watch the talks! pirsa.org/C13015

High energy particle collisions, like the ones produced and studied at the Large Hadron Collider (LHC) at CERN, often produce jets: tight cones of many particles, produced in the collision and all radiating outward in the same direction. The exact structure of these jets can tell physicists much about the forces involved in the collision. Advances are being made in the theory and measurements of jet properties, and jet substructure is a rapidly maturing subject at the LHC. As our understanding of jets improves, jet substructure is a potentially useful tool to search for new physics beyond the Standard Model at the LHC. This high-level workshop focused on progress on the theoretical understanding of the structure of jets in busy hadronic final states, the experimental status of substructure observables, and the applications to searches for new hadronic states at the LHC.

Women in Physics: Past, Present, and Future

March 8, 2013
Watch the talks! pirsa.org/C13016

The "Women in Physics" conference was open to a broad audience, including university students, faculty in physics and science, faculty in the humanities and social sciences interested in gender issues, and members of the general public. Researchers offering their perspective included historians, philosophers, and social scientists who study women in science, as well as physicists from inside and outside of Perimeter Institute.

4-Corner Southwest Ontario Condensed Matter Symposium 2013

April 25, 2013 | Watch the talks! pirsa.org/C13018

This one-day symposium, the sixth in a successful annual series, gathered condensed matter researchers from across southwestern Ontario for informal discussion of their recent research in this rapidly-moving field. Topics covered in this packed day included tensor networks, the properties of exotic new materials and phases of matter, and the future of quantum computing with superconducting circuits. Keynote talks were given by Steve Kivelson of Stanford, who spoke on "Theoretically Established States with a Pseudo-Fermi Surface," and Radu Coldea of Oxford, who spoke on "Reaching Experimentally Quantum Criticality: A Playground to Explore Novel Correlated Quantum States of Matter."

Check perimeterinstitute.ca for conference updates

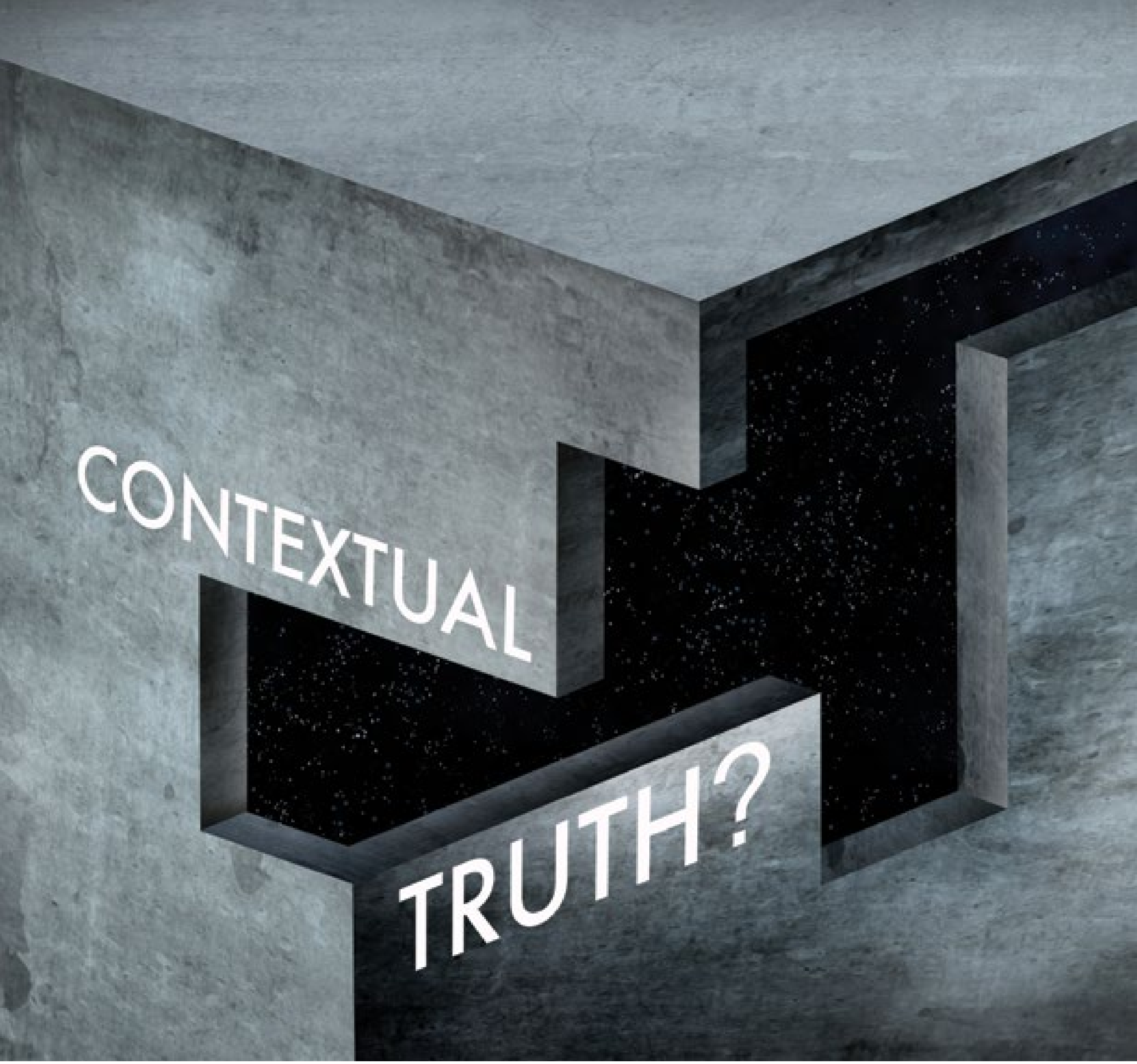
Upcoming Conferences

EMERGENCE AND ENTANGLEMENT II
Monday, May 06, 2013 to Friday, May 10, 2013

THE QUANTUM LANDSCAPE
Monday, May 27, 2013 to Friday, May 31, 2013

COSMOLOGICAL FRONTIERS IN FUNDAMENTAL PHYSICS 2013
Monday, July 08, 2013 to Thursday, July 11, 2013

LOOPS 13
Monday, July 22, 2013 to Friday, July 26, 2013



Consider the following proposition: "At Christmas, it is customary to eat turkey. True or false?" Well, you say, it depends on who you ask. A group of Canadians would say it's true; a group of Italians would say it's false.

Who is right?

The answer is both and neither. This apparent contradiction hinges on the word 'customary.' Each group has taken it as applying to their specific national subgroup of all possible humans. From this simple example, we can start understanding the concept of 'contextual truth' – i.e., the fact that the truthfulness of a statement depends on the *context* in which it is evaluated.

There are many examples of contextual truths in our lives. The example we just gave is an instance of 'spatial contextual truth' – the truth of the statement depends purely on the location of the group: Canada or Italy. On the other hand, if it were possible to ask a group of Canadians living in the year 1500 if it were true that "at Christmas, it is customary to eat turkey," they would probably say no, disagreeing with the contemporary Canadians. In this case, the difference in truth values assigned to the same proposition is due to different time periods, an example of 'temporal contextual truth.'

The concept of contextual truth is important in physics, in particular in quantum theory. The laws of classical physics tell us about how objects in the macroscopic world behave – from water drops to rocks to cars to planets. At this scale, we use classical logic. Quantum theory describes the laws governing the behaviour of very small (micro-scale) particles such as electrons, photons, etc. At this scale, we need to use quantum logic.

To delineate the difference between classical and quantum logic, consider the following two macro propositions: "The car is going at 90 km an hour," and "The car is on the highway." By looking at the car and measuring its speed, we can easily assign truth values to both of these propositions. Now consider the combined proposition: "The car is going at 90 km an hour and it is on the highway." In classical logic, the truth value of the combined proposition is directly deduced from the truth values of the first two propositions; in fact, they can be considered *equivalent*. However, if we go to the quantum world and talk about electrons instead of cars, the situation changes radically.

Consider the analogous micro propositions: "The electron has momentum $\mathbf{x}$," and "The electron has position $\mathbf{y}$." The truthfulness of these propositions can be assessed in a similar manner as for the propositions regarding the car. If we combine the two propositions, we obtain, "The electron has momentum $\mathbf{x}$ and position $\mathbf{y}$." While in classical logic, this would be equivalent to the two separate propositions, in quantum logic, this is not the case. In fact, because of the laws of quantum theory, the proposition, "The electron has momentum $\mathbf{x}$ and position $\mathbf{y}$," is neither true nor false. This is what makes quantum theory and quantum logic so radically different from classical theory and classical logic!

It is precisely here that the notion of contextual truth comes into play. Let's go back to our turkey experiment, with a twist. Now, we join up the two groups to form a bigger group comprised of equal numbers of Italians and Canadians and ask whether the statement "it is customary to eat turkey at Christmas" is true or false. The mixed group cannot give an unambiguous answer. In this new *context*, the proposition is neither true nor false.

This example shows how the choice of contexts can determine whether or not it is possible to assign truth values to propositions. To solve the strange puzzle of quantum logic, what is needed is an appropriate choice of contexts which allows propositions to be evaluated. This gives a range of contextual truth values. The collection of all of them, called the 'global truth value,' is the 'real' truth value.

To obtain the 'global truth value' of the Christmas turkey proposition, we would need to consider all possible appropriately defined contexts – that is, all possible nations (or groups representing different nations). The collection of all their contextual truth values would give the desired global truth value, which allows for more possibilities than plain truth and plain falsity.

It is precisely in this sense that both the Canadian and Italian group of our experiment were right and wrong at the same time: each was right *contextually*, but both were wrong *globally*.

It might seem strange at first to call the collection of contextual truth values a global truth value; however, this strangeness disappears when we realize that contextual truths can actually be related.

For example, nowadays, most English-speaking countries would assign a 'true' value to the Christmas turkey proposition since they share the same Anglo-Saxon heritage. On the other hand, nearly all non-English-speaking countries would assign the 'false' value. Thus, the similarities or dissimilarities of the countries considered would determine whether or not they agree on the truth values assigned.

In this way, the collection of *contextual* truth values reflects the relations of the underlying contexts so that the *global* truth value has the global structure of the collection of all contexts woven into it. Mathematically, the way in which contextual truth values are obtained is by enlarging the set of truth values from {True, False} to a set with many more values.

To understand this, let us again consider the example of the proposition, "At Christmas, it is customary to eat turkey." Now assume we ask a Canadian married to an Italian woman to assess this proposition. The truth value he will assign will be neither true nor false since he and his wife alternate traditions each year. The 'correct' truth value he would give would be 'sometimes.' However, if he and his wife celebrated a Canadian Christmas 70 percent of the time and an Italian Christmas only 30 percent of the time, the 'correct' truth value would be 'most of the time.'

In this way, one can think of a truth value as an indicator which tells you how far away from the complete truth you are. The collection of such truth values forms what is called a 'Heyting algebra' in which all standard logical operations (and, or, not, if, then) are well defined.

Heyting algebras represent the logic present in a branch of mathematics called 'topos theory,' which is widely used in the foundations of mathematics and, in recent years, also in some areas of physics, such as quantum theory.

Next time you assess the truthfulness of a statement, you might unknowingly be using topos theory!

- Cecilia Flori

Cecilia Flori is a postdoctoral researcher at Perimeter.

Is this cube IN or OUT?

Recent Perimeter Publications

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The Sweet Science of Chocolate

Chocolate – it's possibly the world's tastiest polymorph.

A substance that's polymorphic can have several different crystal forms – that is, several different patterns into which molecules can pack, like small triangular tiles arranging in different ways to form either hexagrams or stars.

In the case of chocolate, the fat molecules in cocoa butter have six crystal forms. Only one of these forms – form V – is considered desirable, because its shearing strength gives it 'snap' and its melting point is close to human body temperature – it melts in the mouth, but not on your fingers. It also happens to be glossy. Most commercial chocolate comes pre-tempered and ready to eat. But if you want to make a chocolate coating for anything, you may want to optimize your chocolate's crystal structure.

The Black Hole Bistro's pastry chef, Tracy Smith, recommends this method. You'll need a chocolate thermometer to temper chocolate, but otherwise it's not hard. Try dipping strawberries into it or one of Tracy's own oatmeal chocolate chip cookies.

How to temper chocolate

1. Melt dark chocolate in a clean, dry bowl set over simmering water, to about 115-120°F (46-49°C). Remove the bowl from the heat and let the chocolate cool to around 80°F (27°C).

2. Drop a good-sized chunk of solid (and already tempered) chocolate in to the cooling chocolate. While cooling, stir frequently.

3. The last step is the most important: return the bowl to the heat, bringing the chocolate up to the perfect temperature, where the formation of crystal form V is thermodynamically favoured. This occurs in most dark chocolates between 88° and 91°F (31-32°C.) (Milk chocolate tempers at 86-88°F, 30-31°C. Please note that chocolates can vary, so check with the manufacturer if you're unsure about your particular chocolate.)

4. Remove what's left of the chunk of 'seed' chocolate, and your chocolate is dip-worthy: you can dip all the chocolates you want and all will be perfectly tempered. Don't let it get above 91°F (32°C) or you'll have to begin the process all over again. If it starts to solidify, rewarm it gently to melt.

The pre-tempered chocolate acts as a seed crystal. As the chocolate begins to recrystallize from its liquid state, the exposed edges of this seed crystal will coax other matching crystals to form — rather the way the ragged edge of a half-laid tile floor will force the correct position of the next tiles. The semiconductor industry uses similar techniques to grow large crystals for semiconductor chips.

A cook skilled in condensed matter physics can control which crystal form the chocolate takes by controlling the conditions under which it melts and freezes. Just as in metallurgy, this process is known as tempering.

Unfortunately for kitchen scientists, form V is not the most stable of chocolate's crystal forms. Leave your carefully tempered chocolate in a hot car, letting it melt and re-solidify, and it will be an entirely different experience.

Tracy's Oatmeal Chocolate Chip Cookies

- 1/2 cup butter
- 1/2 cup brown sugar
- 1/2 cup sugar
- 1 egg
- 2 teaspoons vanilla extract
- 1 1/4 cups chocolate chips
- 1 1/3 cups flour
- 1/2 cup large rolled oats
- 1/2 teaspoon salt
- 1/2 teaspoon baking soda

1. Whisk together flour, rolled oats, salt, and baking soda.
2. In a separate bowl, cream together butter and sugars until light and fluffy. Add the egg and vanilla and combine thoroughly.
3. Combine mixtures, only to incorporate, careful not to over mix. Fold in chocolate chips.
4. Chill dough before baking.
5. Bake at 350°F for 12 to 15 mins.

SYNERGY

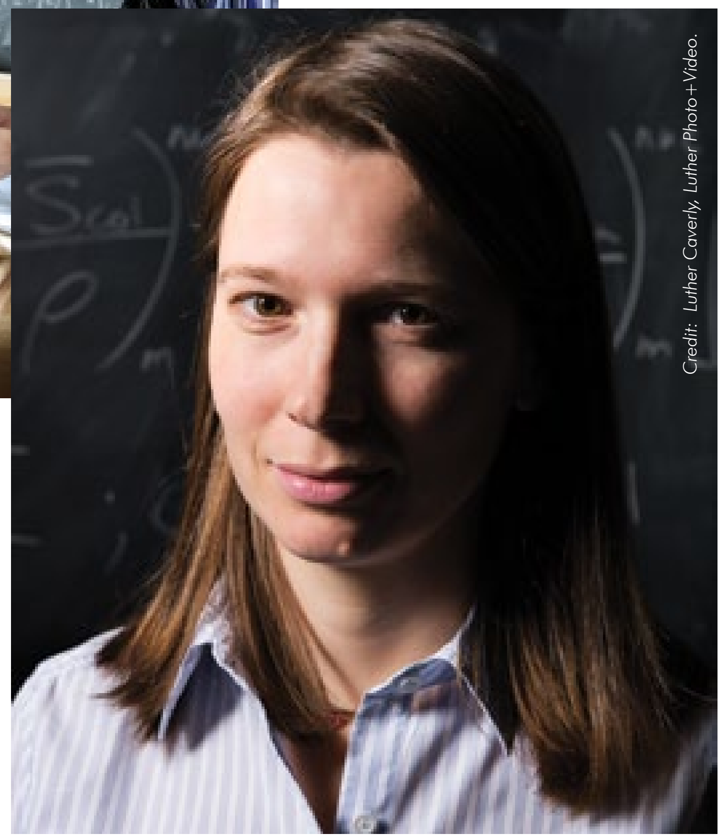
Synergy is a collaborative arts initiative which connects Perimeter Institute researchers with contemporary visual artists to produce and execute site-specific works of art.

Equal Interference

"Equal Interference" by visual artist Soheila Esfahani and Perimeter Postdoctoral Researcher Carlos Tamarit explores the intersection of interior and exterior space through two complementary visual perspectives. This creative collaboration reveals that how we see and interpret our surroundings is a very multi-faceted experience. Often, the convergence of differing viewpoints brings a new clarity. Through this installation, viewers are invited to question their understanding of space and how visual selection and omission can alter one's assessment of the world.

Synergy acknowledges the generous support of Rob Schlegel in developing this project.

Thomson working with colleagues at Perimeter in 2006.



Perimeter Alumna Rowan Thompson is now the Canada Research Chair in Radiotherapy Physics at Carleton University.

Using Physics to Fight Cancer

Rowan Thomson, who did her PhD at Perimeter from 2003 to 2007, is using fundamental physics to fight cancer. Currently an Assistant Professor of Medical Physics at Carleton University in Ottawa – recently appointed as the Canada Research Chair in Radiotherapy Physics at Carleton University – Thomson studies the interactions of radiation and matter. Her work has led to the development of "BrachyDose" – an algorithm that helps doctors give accurate doses of radiation to cancer patients. The algorithm's name refers to brachytherapy, a form of cancer treatment in which radioactive sources are placed next to or inside tumours to eradicate them.

"The motivation for developing BrachyDose was that the current dose calculation method is inaccurate, sometimes 90 percent wrong based on the context," she says. The problem is that current programs "treat the patient like a bucket of water"; using her background studying how radiation interacts with matter, Thomson made sure BrachyDose got the physics right. "We developed a new tool that can very accurately calculate dose and is fast enough to get results in under a minute."

With her background in theoretical physics, Thomson has been able to contribute to the advancement of radiation treatments for cancer. "There's a direct link between my theoretical and computational work and the real world. I'm collaborating with people at the Mayo Clinic in the US and what we're doing informs their medical practice. It's changing the way patients are treated."

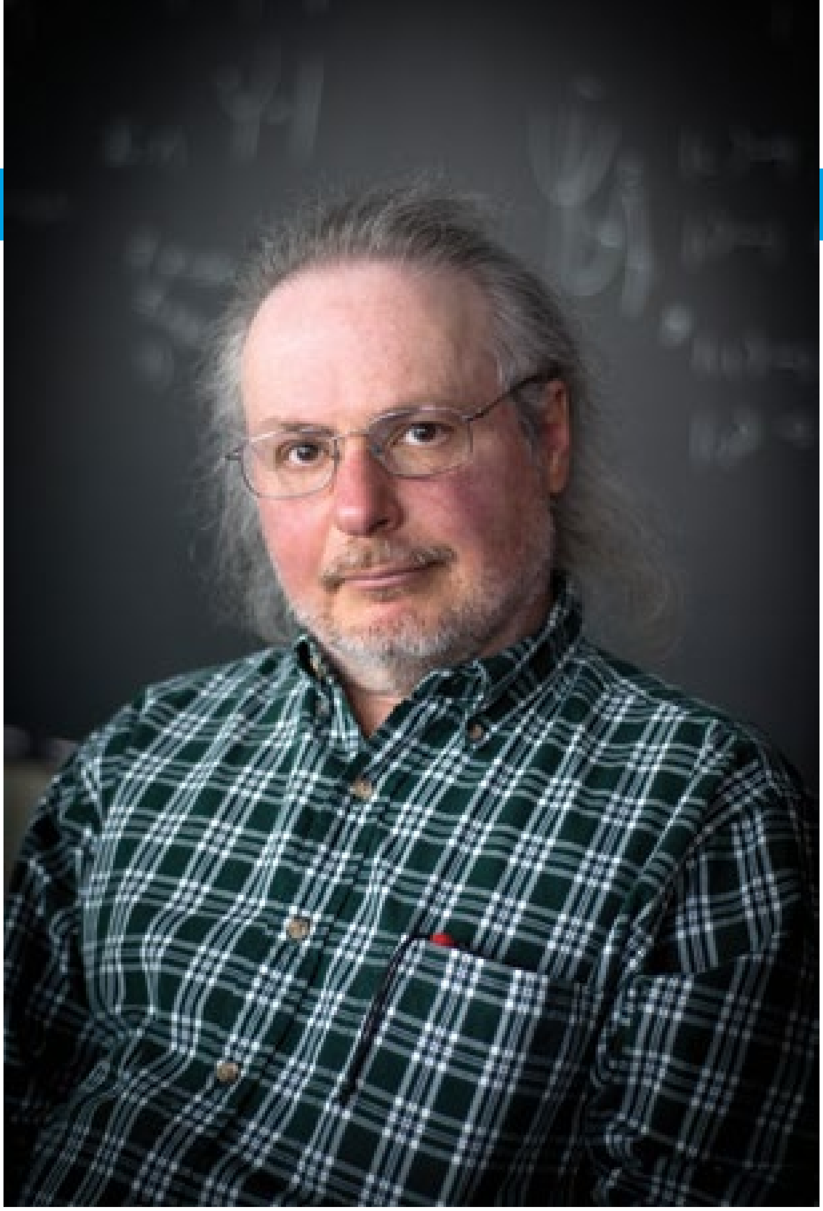
Thomson was awarded the prestigious Polanyi Prize in 2011 for her contributions to physics and she is looking forward to continuing on her research trajectory. "There's a lot of exciting research involving trying to understand radiation interactions with cells, and on very short length scales, where my theoretical background is great."

"In pure theoretical physics, like what's done at Perimeter, you're trying to understand the world around us," she says. "To me, physics is like a good novel; the more you get into it, the more you want to read and the more exciting it gets."

- Phil Froklage

Donor Profile:

Dorian Hausman



Dorian Hausman is a retired computer professional and business owner. A native of Waterloo Region, Hausman retired in 2004 from the Markham-based technology company he co-founded with two colleagues to return to Waterloo. He recently spoke with *Inside the Perimeter* about why he supports the Institute and science in Canada.

Inside the Perimeter: Where did your interest in science begin?

Dorian: I've been fascinated with science for as long as I can remember. My father was a mechanical engineer, so from an early age I was playing with magnets, tinkering with electric motors, things like that. In high school, I remember sneaking into the math and computing centre at the University of Waterloo after school – I was completely hooked on computers. You probably couldn't get away with doing that today, but in the days of punch-card programming, no one was asking me for any account information.

Inside: How did you first get involved with Perimeter Institute?

Dorian: I remember being curious about Perimeter since the announcement and seeing the building go up here in Waterloo. This is the first time I've donated, but I've watched the work here with interest for some time. My wife and I initially signed up for the concerts – we were delighted to see such talented artists so close to home. In 2004, we started attending the lectures and I was immediately hooked. Once, we were vacationing in Europe, and I had to get back from a hike by 3 pm so that I could get online and start clicking to reserve tickets for the next public lecture. I think my wife considered having an intervention after that.

Inside: What prompted you to donate to Perimeter?

Dorian: I think it's the fact that, with Perimeter, I know I'm supporting basic science. I heard a speech from Mike Lazaridis during Einsteinfest – he was talking about why he chose to found the Institute. That speech had a big impact on me – he was talking about making visionary investments now, with a long view to the future. I decided to support Perimeter because I realized that we know there will be breakthroughs, but we don't know where, or when, or how they will manifest themselves in terms of technological advance. We can't even imagine the sorts of technologies that will come – that's not a saying, we literally *can't* imagine it. It's important to solve short-term problems, but someone needs to make those visionary, long-term investments as well. We pay a price for forgetting about that.

Inside: Is that the message you're hoping to convey to other readers?

Dorian: Yes, I think so. I remember one public lecture, where a professor spoke about time – the nature of time. I remember thinking, "This is interesting, but what does this have to do with me? Why is this terribly important?" Then he gave the GPS as an example. A GPS wouldn't be practical if we didn't explore the questions about time that he was asking. Who would have thought that Einstein's work on space and time would one day give us the GPS? Who could have known that was possible? I'd like to get that message across, but also the message that you don't have to have millions of dollars to support the Institute. We all have a stake in a better future, and I think that Perimeter will be an enduring legacy for Canada if we support it now.

- Phil Froklage

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