2012/13 Annual Report to Industry Canada

Covering the Objectives, Activities, and Finances
for the period August 1, 2012 to July 31, 2013 and
Statement of Objectives for Next Year and the Future

Submitted by: Neil Turok, Director
to the Hon. James Moore, Minister of Industry
and the Hon. Greg Rickford, Minister of State (Science and Technology)

Vision: To create the world's foremost centre for foundational theoretical physics, uniting public and private partners, and the world's best scientific minds, in a shared enterprise to achieve breakthroughs that will transform our future.

Overview of Perimeter Institute

"Perimeter Institute is now one of the world's leading centres in theoretical physics, if not the *leading centre."*

– Stephen Hawking

A recent study ranked Perimeter Institute second in research excellence in theoretical physics worldwide, only slightly behind the renowned Institute for Advanced Study in Princeton.[1]

Theoretical physics is the lowest-cost, highest-impact field of science. It seeks to understand what the universe is made of, and the forces that govern it, at the most basic level. Because the field is so fundamental, just one major discovery can literally change the world. The discovery of electromagnetism, for example, led to radio, X-rays, and all wireless technologies, and in turn catalyzed breakthroughs in all the other sciences. The discovery of quantum mechanics led directly to semiconductors, computers, lasers, and a nearly infinite array of modern electronics.

Located in Waterloo, Ontario, Perimeter Institute for Theoretical Physics was founded in 1999, as an unprecedented effort to strategically accelerate discovery in this most basic area of science. Its visionary funding model unites public and private partners, and the world's best scientific minds, in a shared quest to achieve the next breakthroughs, which will transform our future.

As of July 31, 2013, the Perimeter community has grown to include:

- 20 full-time faculty
- 12 associate faculty
- 34 Distinguished Visiting Research Chairs
- 44 postdoctoral researchers
- 70 graduate students[2]

Perimeter is also a major research hub, whose conference and visitor programs bring over 1,000 scientists to the Institute annually, catalyzing new research collaborations and discoveries across the spectrum of fundamental physics.

Breakthroughs in physics are essential to our society and our future. Thus, an integral part of Perimeter's mission is educational outreach to teachers, students, and the general public. The Institute's award-winning programs and resources seek to engage, educate, and inspire, communicating the importance of basic research, the joy of discovery, and the enduring power of ideas.

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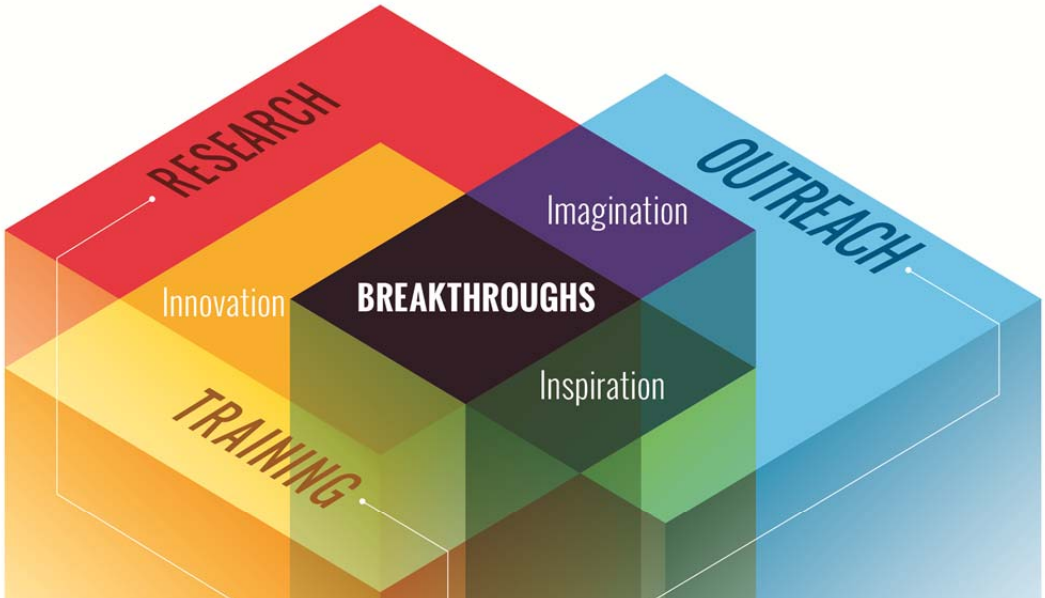
[1] Source: "Ranking and Mapping of Universities and Research-Focused Institutions Worldwide Based on Highly-Cited Papers: A Visualization of Results from Multi-Level Models," http://www.excellencemapping.net/info.html

[2] This includes 39 PhD students and 31 Perimeter Scholars International (PSI) master's students.

AN ECOSYSTEM OF DISCOVERY

GOALS

1. To achieve research breakthroughs that will transform our future
2. To foster the next generation of brilliant physicists
3. To share the transformational power of theoretical physics with the world



150 SCIENTISTS IN RESIDENCE conducting research

11 MAJOR PRIZES awarded to Perimeter scientists in 2012/13

1,000+ VISITING INTERNATIONAL SCIENTISTS annually

2,500+ PAPERS appearing in over 60 journals with 77,000+ citations since 2001

6,700+ ONLINE TALKS and lectures accessed by viewers in 175 countries

14 YEARS after its creation, Perimeter was recently ranked **#2** IN SCIENTIFIC EXCELLENCE in the world in theoretical physics

>2.5 MILLION STUDENTS reached since 2003

8,000+ EDUCATORS trained through Perimeter workshops since 2003

500 TOP HIGH SCHOOL STUDENTS from 44 countries inspired by the International Summer School for Young Physicists since 2003

90 COUNTRIES have broadcast *The Quantum Tamers*, a documentary on new quantum information science

Perimeter is currently home to
70 PHD & MASTER'S STUDENTS and
44 POSTDOCTORAL RESEARCHERS

Perimeter Scholars International (PSI) Master's Program
125 GRADUATES from **37** COUNTRIES since **2009**

Contents

Executive Summary

Perimeter Institute's mission is to create and sustain the world's leading centre for foundational theoretical physics research, training, and outreach, fostering excellence and stimulating major scientific breakthroughs.

Each of the Objectives set out in last year's Corporate Plan plays a part in the Institute's comprehensive long-term strategy for achieving this very ambitious goal. In 2012/13, the Institute made excellent progress toward fulfilling or exceeding major targeted outcomes under all of its Objectives by year's end. This provides strong evidence that the Institute's strategic planning has been both sound and effective, and that it is on track to achieve its long-term vision.

Achievement Highlights, 2012/13

Advancing Fundamental Research

- ✓ A recent international study on research excellence showed that Perimeter Institute ranks fifth in physics overall, and second in theoretical physics globally[3]
- ✓ Advanced fundamental research through 397 high calibre papers
- ✓ Sample research highlights include the following:
    - o Faculty member Dmitry Abanin has developed a general theory of quantum dynamics to describe large systems where quantum effects persist through time. This is a critical prerequisite to understanding how to create and control quantum "many-body" systems. Such systems will likely underpin important future technologies such as quantum computers.
    - o Quantum computing holds potential for ultra-powerful information processing by harnessing quantum phenomena such as superposition and entanglement. To overcome the errors that inevitably arise in fragile quantum systems, Faculty member Daniel Gottesman has proposed a "quantum refrigerator" that enables longer and more reliable quantum error correction – an important step toward practical quantum computing.
    - o Faculty member Kendrick Smith has developed crucial computational techniques which are now being used to analyze and interpret data from the Planck satellite, which is providing major new insights into the structure of the very early universe.

[3] Source: "Ranking and Mapping of Universities and Research-Focused Institutions Worldwide Based on Highly-Cited Papers: A Visualization of Results from Multi-Level Models," http://www.excellencemapping.net/info.html

- ✓ PI researchers won numerous national and international awards and honours, including the following:
    - o Faculty member Kendrick Smith was awarded the Gruber Prize as a member of the Wilkinson Microwave Anisotropy Probe (WMAP) team, which produced a map of the universe's oldest light.
    - o Faculty member Davide Gaiotto was awarded a $100,000 New Horizons in Physics Prize by the Fundamental Physics Prize Foundation.
    - o Distinguished Visiting Research Chair Stephen Hawking was awarded a $3 million Fundamental Physics Prize by the Fundamental Physics Prize Foundation for his seminal contributions, especially to black hole physics.
    - o Associate Faculty member Roger Melko was named a Tier 2 Canada Research Chair and awarded the IUPAP Young Scientist Prize in Computational Physics.
    - o Faculty member Daniel Gottesman and Senior Researcher Christopher Fuchs were elected Fellows of the American Physical Society.
    - o Five Perimeter scientists were awarded the Queen Elizabeth II Diamond Jubilee Medal.
    - o Faculty members were awarded over $2.3 million in research grants.

Attracting the Best

- ✓ Re-appointed Director Neil Turok to a second five-year term at Perimeter's helm and appointed him to the Mike and Ophelia Lazaridis Niels Bohr Chair in Theoretical Physics
- ✓ Appointed Dmitry Abanin, Luis Lehner, and Kendrick Smith to Perimeter's faculty
- ✓ Appointed 12 eminent international scientists as Distinguished Visiting Research Chairs
- ✓ Jointly recruited Matthew Johnson with York University and Roger Melko with the University of Waterloo as associate faculty members
- ✓ Hired 20 postdoctoral researchers in 2012/13 and recruited an additional 18 for 2013/14

Training the Scientists of the Future

- ✓ Trained 29 students from 15 countries, including 10 women, through the Perimeter Scholars International (PSI) master's program
- ✓ Trained 39 PhD students
- ✓ PhD graduates Jorge Escobedo and Cozmin Ududec founded new Canadian companies: Toronto-based Canopy Labs, helping businesses predict consumer behaviour and target sales through data analysis, and Winnipeg-based Invenia Technical Computing, quantifying and managing financial risk in energy arbitrage markets
- ✓ Six departing postdoctoral researchers obtained tenure-track faculty positions

A Global Hub for Scientific Interaction

- ✓ Forged new partnerships with TRIUMF and SNOLAB, Canada's labs for particle and dark matter physics; with the Weizmann Institute of Science in Rehovot, Israel; and with the International School for Advanced Studies (SISSA) in Trieste, Italy
- ✓ Provided expertise to the African Institute for Mathematical Sciences – Next Einstein Initiative (AIMS-NEI)
- ✓ Held 10 conferences and workshops, attended by nearly 700 scientists from around the world
- ✓ Presented 301 scientific talks (257 seminars, 44 colloquia)
- ✓ Hosted 432 visiting scientists to do collaborative and individual research
- ✓ Shared the Institute's scientific events virtually with 81,099 visitors from 170 countries via the Perimeter Institute Recorded Seminar Archive (PIRSA), up 7.5 percent over the previous year

Inspiring Through Outreach

- ✓ Reached over one million students with PI educational resources
- ✓ Neil Turok delivered the 2012 CBC Massey Lectures across Canada and through broadcast online and on CBC Radio One; the book of the lectures, *The Universe Within: From Quantum to Cosmos,* was awarded the Lane Anderson Prize for outstanding popular science writing
- ✓ Produced a new Perimeter Explorations module, *Career Moves: Skills for the Journey*, designed to show high school students the exciting career possibilities that science and math-based fields offer
- ✓ Hosted the 11th annual International Summer School for Young Physicists for 40 Canadian and international students
- ✓ Held five GoPhysics! camps and gave 10 Physica Phantastica presentations to over 2,200 students across Canada
- ✓ Delivered more than 90 teachers' workshops, reaching more than 2,500 educators and 125,000 students
- ✓ Delivered Perimeter content to 1,500 Aboriginal youth in 60 rural and remote communities in partnership with Actua and the Indigenous Education Coalition
- ✓ Presented 10 sold-out public lectures

Creating an Optimal Research Environment

- ✓ Enhanced Perimeter's IT systems and library collections, providing state-of-the-art computing and research resources to scientists

Growing the Public/Private Partnership

- ✓ Attracted over $1.6 million from individuals, corporations, and foundations
- ✓ Launched the Corporate Partners Program, Emmy Noether Circle, and Friends and Alumni Program
- ✓ Secured $100,000 to create the Anaximandros Scholarship for exceptional young physicists

Perimeter in the News

- ✓ Branded Canada and Perimeter through major media coverage including *The Globe and Mail*, *National Post*, *Toronto Star*, *Maclean's*, *The Huffington Post*, CTV, CBC, *Nature*, *The Walrus*, *TIME Magazine*, *Reader's Digest*, *Wired UK*, and *The Economist*, among others.

"[Neil Turok] has been instrumental in developing Perimeter's reputation as one of the world's leading centres for cutting-edge theoretical physics as well as public outreach. Unlocking the secrets of the universe is not enough; at Perimeter, they want everyone to share in the joy of discovery."
– "The God Particle," *The Walrus*, December 2012

"In less than 15 years, a global hub for quantum research has been created from almost nothing in Waterloo Region. It includes: the largest theoretical physics institute in the world, the most state-of-the-art labs ever built to fabricate quantum devices and hundreds of researchers recruited from around the globe. Spinoff companies are being created, patents are being filed and luxury hotels and restaurants are springing up to service an incoming scientific class. Quantum is becoming a household word for the general public, who are lapping up science lectures at surprising rates."
– "The quest for Quantum Valley," *The Waterloo Region Record*, April 20, 2013

Statement of Objectives for 2012/13

Objective 1: To deliver world-class research discoveries

Objective 2: To become the research home of a critical mass of the world's leading theoretical physicists

Objective 3: To generate a flow-through of the most promising talent

Objective 4: To become the second research home for many of the world's outstanding theorists

Objective 5: To act as a hub for a network of theoretical physics and math centres around the world

Objective 6: To increase Perimeter's role as Canada's focal point for foundational physics research

Objective 7: To host timely, focused conferences, workshops, seminars, and courses

Objective 8: To engage in high impact outreach

Objective 9: To create the world's best environment and infrastructure for theoretical physics research, training, and outreach

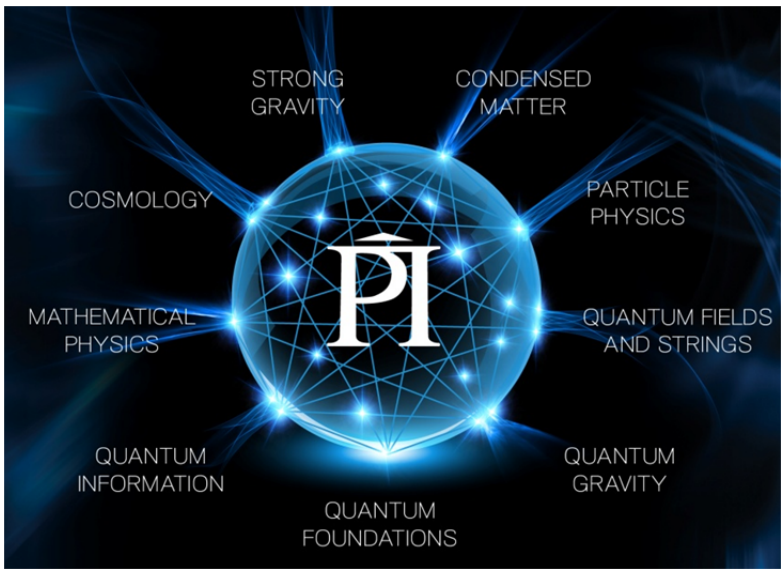
Objective 10: To continue to build on Perimeter's highly successful public/private partnership funding model

Objective 1: To deliver world-class research discoveries

Summary of Achievements

- Advanced fundamental research through 397 high calibre papers
- Since inception, PI researchers have produced 2,548 papers appearing in over 60 journals, which have attracted 77,412 citations to date, attesting to the importance and long-term impact of PI research

Highlights

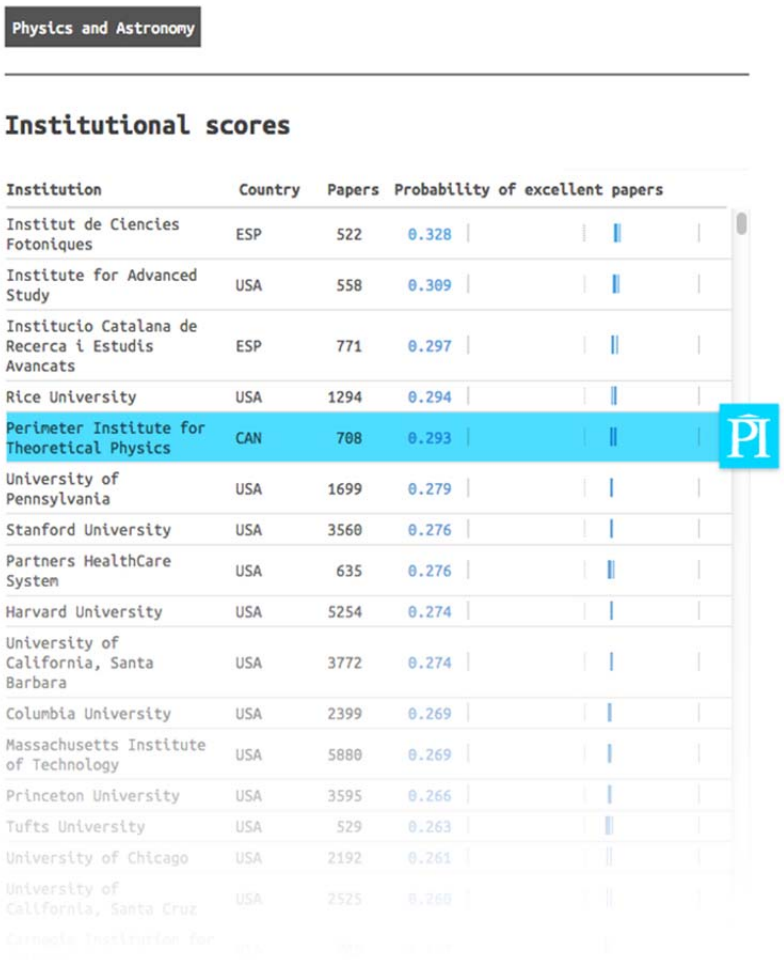


The Scientific Excellence Map

In a recent study, "Mapping Scientific Excellence," Perimeter Institute was ranked fifth overall in the world in physics – and **second in theoretical physics** – behind only the renowned (and venerable) Institute for Advanced Study in Princeton, and above such traditional centres of excellence as Harvard, Stanford, and MIT. The next Canadian institution to appear on this list is ranked 78th.

The study was led by researchers at the Max Planck Institute in Munich, who analyzed publication data gathered from Scopus, the world's largest abstract and citation database for peer-reviewed literature. Using this data, they estimated the probability of an institution's researchers publishing papers belonging to the top 10 percent of most-cited papers within their subject categories, providing an

accurate proxy for research excellence.[4] The study's methodology has been lauded for its objectivity, since it relies only on publication data, rather than on hard-to-measure factors such as reputation or third-party opinion. (For more detailed results from the study, refer to Appendix A: Top 100 Physics and Astronomy Institutions Worldwide, Drawn from Excellence Map Analysis.)



Physics and Astronomy

Institutional scores

Institution	Country	Papers	Probability of excellent papers
Institut de Ciencies Fotoniques	ESP	522	0.328
Institute for Advanced Study	USA	558	0.309
Institucio Catalana de Recerca i Estudis Avancats	ESP	771	0.297
Rice University	USA	1294	0.294
Perimeter Institute for Theoretical Physics	CAN	708	0.293
University of Pennsylvania	USA	1699	0.279
Stanford University	USA	3560	0.276
Partners HealthCare System	USA	635	0.276
Harvard University	USA	5254	0.274
University of California, Santa Barbara	USA	3772	0.274
Columbia University	USA	2399	0.269
Massachusetts Institute of Technology	USA	5880	0.269
Princeton University	USA	3595	0.266
Tufts University	USA	529	0.263
University of Chicago	USA	2192	0.261
University of California, Santa Cruz	USA	2525	0.260

Fig. 1: Ranking and Mapping of Universities and Research-Focused Institutions Worldwide Based on Highly-Cited Papers: A Visualization of Results from Multi-Level Models. (Refer to arxiv.org/abs/1212.0304 and http://www.excellencemapping.net/info.html.)

[4] The tool analyzed publications from institutions that published at least 500 articles, reviews, and conference papers in the period 2005 to 2009 in 17 subject areas (e.g., Physics and Astronomy or Materials Science), as defined by Scopus. The citation window is from publication until the end of 2011. The research was led by Professor L. Bornmann (Division for Science and Innovation Studies, Administrative Headquarters of the Max Planck Society, Munich, Germany). A paper detailing the full methodology is available at http://arxiv.org/abs/1212.0304.

Quantum Information

Quantum computers, which capitalize on quantum effects such as "superposition" and "entanglement" to achieve processing power far surpassing present-day computers, are expected to revolutionize how we work, communicate, and live. Much theoretical research is required, however, before these technologies can emerge. Perimeter researchers explore quantum error correction – the techniques needed to safeguard and verify information amid the errors inherent to quantum computation. Researchers also pursue the foundations of quantum cryptography, which capitalizes on uniquely quantum laws – such as the uncertainty principle – to safeguard private information. Many of Perimeter's quantum information researchers collaborate with scientists at our nearby experimental partner, the Institute for Quantum Computing (IQC), and some hold joint appointments at both institutes. Together, Perimeter and IQC are transforming the region into the world's "quantum valley."

Chill Out, Qubits!

To err is quantum.

When wrangling the quantum building blocks of nature to perform information processing, mistakes are bound to happen. Quantum information is very powerful, but also very fragile.

Processors that function according to quantum laws have the potential to be vastly more powerful than even today's most complex supercomputers, but the realization of that potential will hinge on how researchers understand and deal with the errors that inevitably arise during quantum computation.

Perimeter Faculty member Daniel Gottesman is a pioneer in fault-tolerant quantum computation, by which reliable computation can happen if the error rate is kept below a given threshold.

To keep that error rate low, Gottesman and collaborators Michael Ben-Or (Hebrew University of Jerusalem) and Avanitan Hassidim (Bar-Ilan University) have proposed a system called a "quantum refrigerator."

It's a fitting name for a proposed system that gives overheated quantum bits (qubits) a place to chill out before being re-used for error correction.

Quantum error correction often requires that secondary qubits – called ancilla qubits – be utilized to measure information about errors in a quantum computation. Typically, this measurement scrambles the ancilla qubits, making them useful for only a single measurement.

Gottesman and collaborators, however, propose a model whereby used ancillas are shunted into a "refrigerator" where they can cool down, unscramble, and potentially be used again. It's a continual loop of heating and cooling that allows for quantum error correction to be performed longer and more reliably than in the past.

It is, therefore, a crucial step toward stable, reliable quantum computation – the driving motivation behind quantum information research.

A Universal Toolkit

Of course, quantum error correction is just part of the puzzle. A quantum computer needs stuff to compute – and stuff to compute it with.

Quantum gates are the quantum equivalent of the logic gates in a classical computer. They are the fundamental building blocks of quantum circuits – the "atoms" of quantum computation, in a sense.

In theory, a quantum algorithm (the instructions a computer follows) might use an enormous variety of different quantum gates. The set of possible quantum gates must be "universal" – that is, the various gates allowed in the system can be arranged to closely approximate any gate that might be needed.

However, they must also be fault-tolerant, in order to cope with real-world errors and imprecision. Thus, in reality, the hardware will have a smaller set of built-in gates that enable fault-tolerant quantum computation.

In order to implement a quantum algorithm on a real quantum computer, one must decompose the gates used in the ideal algorithm into the gates that can be implemented fault-tolerantly on the actual hardware.

The most commonly studied fault-tolerant universal gate set consists of the so-called Clifford gates and what is known as the T gate, with the T gate by far the most costly.

Until recently, the state-of-the-art method for synthesizing a given one-qubit gate into a given fault-tolerant gate set was the celebrated Solovay-Kitaev algorithm. In order to obtain an approximation of a given gate with n digits of precision, the Solovay-Kitaev algorithm produced a circuit with over n^3 fault-tolerant gates.

Perimeter Associate Faculty member Michele Mosca, with collaborators Vadym Kliuchnikov and Dmitri Maslov, discovered a much better method for building any gate from a commonly used fault-tolerant set of gates, producing a circuit with on the order of n gates in order to obtain n digits of precision. Interestingly, this method required the use of an efficient algorithm for finding solutions to the Lagrange 4-squares theorem, which states that any integer N can be decomposed into the sum of at most four perfect squares. For example, $39 = 1^2 + 2^2 + 3^2 + 5^2$.

By requiring much fewer gates than the previous state-of-the-art, this new method allows a quantum algorithm to run much faster – an important innovation toward real-world quantum computing.

The quantum information revolution promises to transform technology and the fundamental research conducted at Perimeter is helping to pave the way to that quantum future.

References:

M. Ben-Or (Hebrew University), D. Gottesman (Perimeter Institute), and A. Hassidim (Bar-Ilan University), “Quantum Refrigerator,” arXiv:1301.1995.

V. Kliuchnikov (Institute for Quantum Computing), D. Maslov (National Science Foundation), and M. Mosca (Perimeter Institute and Institute for Quantum Computing), “Practical approximation of single-qubit unitaries by single-qubit quantum Clifford and T circuits,” arXiv:1212.6964.

Mathematical Physics

In mathematical physics, new problems in physics give rise to new mathematics to solve them and new mathematics open doors to new understanding of the physical universe. Newton invented modern calculus because he needed it to understand mechanics – and calculus went on to redefine all of physics. The development of quantum theory in the 20th century both spurred and was spurred by advances in mathematical fields such as linear algebra and functional analysis. Perimeter's mathematical physics researchers continue this grand tradition.

The New Face of Feynman Diagrams

Scattering amplitudes, which predict what happens when two or more particles interact, are the most fundamental calculation in particle physics. For decades, these calculations have been done using Feynman diagrams. Unfortunately, though, using Feynman diagrams to model even simple collisions of a few particles can involve thousands of diagrams, each introducing many terms into the calculation. As collisions become more complex, the Feynman diagram technique becomes too unwieldy to use.

Now, an international team of researchers, including **Perimeter Faculty member Freddy Cachazo**, has come up with a different and much more user-friendly approach to calculating scattering amplitudes. A landmark paper on the subject, the culmination of a decade of effort, has already attracted widespread attention in the physics community and will likely be a focal point for years to come.

The new system is simpler because it eliminates the great source of redundancy in Feynman diagrams: introduction of off-shell or virtual particles. The new system replaces Feynman diagrams with on-shell diagrams, which use only on-shell particles.

Underlying this new system is the team's discovery of elegant and surprising mathematical structures that govern scattering amplitudes. This work may provide clues that will lead to a much deeper understanding of how elementary particles arise, and perhaps the structure of spacetime itself.

It is a prime example of the kind of research that Perimeter fosters – it is both foundational and extremely ambitious. Over the last several years, faculty members, postdoctoral researchers, and a Distinguished Visiting Research Chair have all contributed to it, and Perimeter has emerged as a leading centre on new approaches to scattering amplitudes.

For his pioneering work, Cachazo won the illustrious 2013 New Horizons in Physics Prize from the Fundamental Physics Prize Foundation for "uncovering numerous structures underlying scattering amplitudes in gauge theories and gravity."

The Origami of Quantum Field Theory

Perimeter Faculty member Davide Gaiotto plays with quantum field theories the way an origami artist plays with paper – folding up flat sheets to make round objects, collapsing round objects back to flat, moving between the dimensions, and discovering whole classes of objects no one has ever seen before.

Quantum field theories, or QFTs for short, are the language in which modern physicists describe nearly all physical systems. They are essential to fields from particle physics to condensed matter to advanced electronics. But as much as we know about QFTs, there is still a lot to learn. In the last five years, thanks to Gaiotto and others, physicists have learned that the QFTs that they can define and study are only a small corner in the much wider space of all possible QFTs.

Gaiotto is out to chart that space.

His master "origami figures" are a small set of six-dimensional field theories, discovered in the 1990s but still mostly mysterious. Starting from that 6-D theory, he has discovered procedures for folding them into simpler forms with fewer dimensions. This is important both because discovering new theories helps chart the wider space of theories and because it is thought that theories with fewer dimensions more closely approximate our world.

The procedure is analogous to this: Consider a two-dimensional theory that exists on a sheet – then roll up the sheet to get a tube. Look at the tube from far away and it is a line – you have dropped a dimension.

Similarly – though this is mind-bending to picture – you can consider a three-dimensional theory which gets "rolled" into a two-dimensional shape. There are several ways to roll it: into a hollow sphere, or into a hollow donut shape or torus, for instance. Those shapes – the sphere and the torus – are called manifolds. Extend either manifold and look at it from some distance and you again get a line. But the theory of the line you reached via a sphere is different from the theory of the line you reached via a torus.

Knowing the path, in other words, tells us important things about the destination. And having new paths lets us find new destinations.

Knowing that the 6-D theory exists and having a procedure to fold away the dimensions allowed Gaiotto to generate immense classes of 3- and 4-dimensional theories, each labeled by the manifold used in the folding. Some of these theories are the familiar ones that have long been known about. But some are new and could not have been discovered in any other way.

References:

N. Arkani-Hamed (Institute for Advanced Study), J.L. Bourjaily (Harvard University), F. Cachazo (Perimeter Institute), A.B. Goncharov (Yale University), A. Postnikov (Massachusetts Institute of

Technology), and J. Trnka (Princeton University), “Scattering Amplitudes and the Positive Grassmannian,” arXiv:1212.5605.

T. Dimofte (Institute for Advanced Study), D. Gaiotto (Perimeter Institute), and R. van der Veen (Korteweg-de Vries Institute for Mathematics), “RG Domain Walls and Hybrid Triangulations,” arXiv:1304.6721.

Cosmology

Cosmologists at Perimeter Institute seek to uncover the distant history and constituents of our universe and decode the rules that govern its origins and evolution. These researchers look for answers to some of the most enduring questions in physics, at scales and energy levels that could never be simulated in an earth-bound lab. Cosmology is intrinsically connected to other branches of research at Perimeter, including particle physics, quantum fields and strings, and strong gravity.

The First Self-Portrait

It could be said that the universe took a "selfie." Like someone holding a camera at arm's length and snapping a self-portrait, the universe took a picture of itself during its infancy.

This picture is, more accurately, the cosmic microwave background (CMB), the oldest light in the universe, imprinted like a photographic negative onto the sky when the universe was a mere 380,000 years old (practically a newborn, considering it is now nearly 14 billion years old).

Thanks to sophisticated telescopes, we can now look at this baby picture of the universe and make out – by interpreting tiny fluctuations in the background that represent areas of different densities – the seeds from which all the stars and galaxies emerged.

Perimeter researchers including **Faculty member Kendrick Smith** seek to interpret and explain the universe's distant past by probing clues left behind by the cosmic microwave background.

Scouring new data from the Planck Satellite mission, Smith and collaborators have examined whether tiny density ripples in the early universe are best described by so-called Gaussian (or bell-curve) statistics or by non-Gaussian statistics – a question posed in numerous competing theories.

In a frequently cited landmark paper, Smith and co-authors determined that the data are indeed Gaussian, providing a clearer new lens through which scientists can examine our earliest image of the universe.

Pinning Down Gravity

While our understanding of the early universe is continually coming into sharper view, many mysteries persist about the present universe.

Perimeter has long been at the centre of the search for plausible modifications to Einstein's theory of general relativity that reconcile with what is now known about dark energy and dark matter, which are generally believed to constitute 95 percent of the universe.

The search for such modifications to general relativity has proven difficult, but an important step was made in 2011 when former **Perimeter postdoctoral researchers Claudia de Rham** and **Andrew Tolley** were part of a team that discovered the full non-linear theory of massive gravity.

This breakthrough sparked the search for a "partially massless" theory of gravity, which yielded a tantalizing result achieved by de Rham, Tolley, and current **Perimeter postdoctoral researcher Kurt Hinterbichler**. The authors demonstrated that the simplest possibility – a partially massless theory of a single graviton – does not exist.

This result has spurred a multi-faceted effort to find, or eliminate the possibility of, a partially massless theory of gravity. Such a theory, if it exists, would provide a new type of solution to the problem of dark energy.

The answers to such big questions will cast new light on the nature of our universe, just as the universe itself has cast its own ancient light, the cosmic microwave background, onto us.

References:

K. Smith (Perimeter Institute) et al., "Planck 2013 Results. XXIV. Constraints on primordial non-Gaussianity," arXiv:1303.5084.

C. de Rham (Case Western Reserve University), K. Hinterbichler (Perimeter Institute), R. Rosen (Columbia University), and A. Tolley (Case Western Reserve University), "Evidence for and Obstructions to Non-Linear Partially Massless Gravity," *Phys. Rev. D* 88, 024003 (2013), arXiv:1302.0025.

Strong Gravity

From the big bang to neutron stars and black holes, Perimeter research into strong gravity explores cosmic cataclysms powerful enough to warp the fabric of spacetime. These areas of space where gravity is extremely strong serve as a natural experiment where researchers can theoretically "test" the validity of our current theory of gravity (Einstein's general relativity) and investigate alternative theories. Perimeter researchers also seek to understand and characterize the ways that curved or dynamical spacetimes are connected to other fundamental questions of physics.

Escape From the Black Hole

It is a cosmic monster of almost unfathomable power.

Gobbling up anything that dares come near it – even light – the black hole at the centre of an elliptical galaxy called Messier 87 (M87) never relinquishes a victim.

It is more than six billion times more massive than our sun. It is 50 million light years from Earth. Nothing that crosses its "point of no return," the event horizon, can escape its grasp.

Peering over this precipice with an enormous network of connected telescopes, a team of international scientists including **Perimeter Associate Faculty member Avery Broderick** has, for the first time ever, measured the event horizon of a black hole outside of our galaxy.

The team observed that the M87 black hole blasts collimated (that is, narrow and extremely fast) jets of material at velocities approaching the speed of light, dramatically altering the environment around it.

The observations – made by linking radio telescopes in Hawaii, Arizona, and California to create a highly precise eye on the cosmos called the Event Horizon Telescope – are the first to capture this jet-launching region of a black hole.

Such measurements, combined with follow-up work that will link even more radio telescopes worldwide, will provide crucial insights into the origins, evolution, and fates of these voracious cosmic giants.

On a Collision Course

Whereas Broderick and his international collaborators have tracked the cataclysmic force of a massive black hole, **Perimeter Faculty member Luis Lehner** has, in a sense, listened for the birth cries of black holes.

Lehner and collaborators studied how two compact objects in a binary system, such as black holes or neutron stars, combine to create a single new entity.

In some cases, a neutron star orbiting a black hole gets swallowed up by its neighbour's gravitational pull; sometimes, two neutron stars spiral ever closer to one another before violently colliding to create a new black hole.

The gravitational force behind both events is tremendously powerful, packing masses equivalent to that of the sun into spheres smaller than most cities; electromagnetic forces create powerful electromagnetic signals.

Such forces create distortions in spacetime that ripple with gravitational waves, and the violent collisions induce the emission of electromagnetic radiation as matter is heated to extreme temperatures and the surrounding plasma becomes accelerated.

Though these ripples have never been directly observed, new detectors may soon change that – and Lehner's research into the mergers of compact objects indicates there are excellent chances of receiving more than one type of signal from these events.

In particular, what Lehner and his colleagues have done is show how two signals – the gravitational wave and the electromagnetic radiation from the system – might be related. Analyzing these two kinds of signals allows astronomers and physicists to cross-check data for comparisons and predictions.

With such crucial information at their disposal, researchers could predict the next cosmic cataclysm and point their telescopes accordingly to catch a gamma ray burst – the beginnings of a black hole – in action.

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Condensed Matter

The challenge of condensed matter physics can be summed up in a single observation: the behaviour of a system with many particles can be very different from that of the particles that make it up. Condensed matter physicists are those who study these many-body systems, especially those that are in a condensed state. At Perimeter, these researchers tackle such fundamental issues as the nature of magnets or the difference between conductors and insulators, as well as cutting-edge questions such as whether we can describe gravity as a property of a material, or tailor an exotic form of quantum matter for use inside quantum computers.

A New Periodic Table for Phases of Matter

What if we needed a new periodic table?

The periodic table – a staple of classroom walls and first-year chemistry textbooks – classifies the elements and predicts their behaviour. In its early days, though full of gaps, it was powerful enough to predict what should fall in each hole and flexible enough to subsume every new discovery. It has shaped and defined chemistry for almost 150 years.

The equivalent of the periodic table in condensed matter physics is the Landau paradigm, which classifies the phases of matter based on the layout and interaction of their constituent parts – technically speaking, their symmetry. As the periodic table did for the elements, Landau guides researchers in discovering new phases of matter and helps them grapple with the behaviours of the known phases.

But in the 1980s, something was discovered that fell off Landau's table entirely: phases of matter that were different from each other, but had the same symmetry. In 1989, **Perimeter Faculty member Xiao-Gang Wen** (then at MIT) made a landmark step forward when he discovered that these new states contained a new kind of order: topological order. In topological order, the phases are not described by the patterns of symmetry, but by the patterns of a quantum property called entanglement.

Since discovering and defining topological order, Wen has been developing new mathematical theories. His goal has been to develop a new system, a new table, which would allow condensed matter researchers to understand all possible topological orders and gain insight into the mysteries of quantum entanglement. In 2012, he finally succeeded.

The trick was to use a very abstract mathematical theory called group cohomology theory.

"It was like history repeating itself," says Wen. "More than 70 years ago, the abstract group theory was introduced into physics to describe phases of matter via their symmetry patterns. Now, the abstract group cohomology theory is introduced into physics to describe phases of matter via their entanglement patterns."

The result was a new classification system that can handle most known phases of matter. This system can be used to generate insight about quantum phases of matter, which may in turn increase our ability to design states of matter for use in superconductors or quantum computers.

The New Laws of Quantum Dynamics

Physicists do not know much about how large quantum systems evolve over time. Until now, they've never needed to.

Quantum systems tend to be small, not large. When lots of atoms get together, quantum effects tend to vanish quickly. Technically speaking, they dissipate into the environment. Once that happens, the system looks classical, and can be described using statistical mechanics.

Recently, though, this has changed. It has become possible to create and study artificial many-body quantum systems – that is, systems containing a large number of atoms, isolated from the environment, in which quantum effects persist over time.

From observing these systems, researchers learned that they do not obey the conventional laws of statistical mechanics, which ordinarily govern systems with large numbers of variables. It became obvious that physics needed a theory of quantum dynamics in place of statistical mechanics. **Faculty member Dmitry Abanin** has just developed one.

Abanin worked with Maksym Serbyn (a graduate student at MIT and a Perimeter visitor) and **Zlatko Papić** (now a Perimeter postdoc) to describe not just the dynamics of a particular quantum system, but to define general laws of quantum dynamics, which can be applied to any experimental quantum many-body system. These laws are expected to be of widespread use as researchers create and study more such systems.

The laws are quite different than statistical mechanics, but they are also unexpectedly simple. They are deeply connected to questions in quantum information, statistical mechanics, and condensed matter.

One immediate result is a counterintuitive one. While we normally think of quantum systems as needing to be cold and pure and isolated, the new laws show that "quantum-ness" can thrive on disorder. Introducing disorder into a quantum many body system can actually increase the coherence times – that is, the length of time quantum effects persist before washing away. Results like these are expected to be vital as scientists work to engineer the first generation of quantum materials for use in quantum information processing devices.

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Particle Physics

Particle physics is the science which identifies nature's constituents and interactions at the most fundamental level. As such, it has strong overlaps with string theory, quantum gravity, and cosmology. At Perimeter, particle physics researchers often compare theoretical ideas with both astrophysical observations and earth-bound experiments like the ones carried out at the Large Hadron Collider, and study how such results can help us map the physics beyond the Standard Model.

A New Spin on Long-Range Forces

There is a hole in our understanding of long-range forces, and **Faculty members Philip Schuster and Natalia Toro** are out to fill it.

Our universe contains two known forces that can reach across galaxies: electromagnetism and gravity. They are both mediated by massless particles – the photon for electromagnetism, the graviton for gravity.

Photons and gravitons (and many other particles) have an intrinsic quality called spin. It is an imperfect analogy, but you can think of spin as nature's smallest bar magnet: it gives the particles something like a north and a south pole, which can point in any direction. When spin is aligned with momentum, it is also called helicity. Spin can have various magnitudes, and so helicity can too: particles can be helicity-1, helicity-2, helicity-3, and so on.

It is also well known that the nature of forces mediated by massless particles is determined by the helicity of those particles. For instance, the fact that electric charges also feel magnetic forces falls naturally out of modelling it with helicity-1 particles. The symmetries of gravity are a consequence of modelling it using helicity-2.

In the 1960s, Steven Weinberg showed that particles with higher helicities (helicity-3 and up) cannot mediate forces. Left open – though rarely noticed – was the possibility that long-range forces could be mediated by particles whose helicity can have any (quantized) magnitude. Such particles are called continuous spin particles, or CSPs. For a variety of reasons, it has been widely assumed that CSPs don't mediate long-range forces, but this assumption remained untested until Schuster and Toro began their work in 2011.

Starting from scratch, using only the basic assumptions of relativity and quantum mechanics as inputs, Schuster and Toro began to develop a model of long-range forces mediated by CSPs. They have uncovered evidence that CSPs are far more consistent, theoretically and phenomenologically, than was previously assumed.

In fact, their findings raise the exciting possibility that the known forces could be mediated by CSPs. Because the helicity of force carriers determines the nature of the force, this would mean that our

understanding of forces would change in subtle and interesting ways. This has potential to be a true breakthrough in our understanding of long-range forces in nature.

Is Space Foamy?

A new idea put forward by **Faculty member Maxim Pospelov** suggests that Earth might be crashing through bubble after bubble in a foamy cosmos – and, crucially, that we might be able to detect bubble walls as we pass through them.

The hypothesis that space might be foamy is not new. It begins with a hypothetical field which has several possible ground states. In the hot chaos of the early universe, this ground state value would have been jumbled, with every point having a different ground state. As the universe expanded and cooled, large regions of space would have settled on a single value. Since then, they would have "frozen" into place, in a kind of invisible cosmic foam. The energy locked into these structures could contribute to those mysterious substances, dark matter and dark energy.

In the recent research, Pospelov estimated the size of the domains in the cosmic field – the bubbles in the foam. He found that the bubbles are small enough that the known speed of our solar system would cause it to pass through many domain walls over the course of a few years. Wall crossing events, then, would be rare, but not impossibly so.

As the Earth passes through a bubble wall, there would be a small and sudden change in the magnetic torque exerted by the hypothetical field. Pospelov and his collaborators predict that the strength of that effect would be about a billionth of the Earth's magnetic field over a millisecond. The current generation of magnetometers are just sensitive enough to pick up such a signal. The team proposed deploying a network of widely separated but synchronized devices, to allow the tiny signals to be cross-checked. A pilot project to develop this detector has been funded by the National Science Foundation (US).

The collaboration, then, has taken two small things – new calculations about the relatively small size of cosmic bubbles and the new small signals that can be picked up by today's magnetometers – and put them into one big new idea: the cosmic foam hypothesis can now be directly tested for the first time.

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Quantum Fields and Strings

Quantum field theory is the modern paradigm with which we understand particle physics, condensed matter systems, and many aspects of early universe cosmology. It is used to describe the interactions of elementary particles, the dynamics of many-body systems, and critical phenomena, all with exquisite accuracy. Perimeter researchers are producing world-leading advances in quantum field theories.

String theory is a theoretical framework which was proposed to produce a unified description of all particles and forces in nature, including gravity. It is based on the idea that at very short distances, all particles should in fact be seen to be extended one-dimensional objects – that is, "strings." Modern string theory has grown to be a broad and varied field of research with strong connections to quantum gravity, particle physics, and cosmology, as well as mathematics.

The Soap-Bubble Solution

What can soap bubbles teach us about quantum field theory? A lot, as it turns out.

Perimeter **Faculty member Pedro Vieira**, former **postdoc Benjamin Basso** (now at EHS) and former **postdoc Amit Sever** (now at the Institute for Advanced Study) have solved a longstanding problem in quantum field theory by mathematically cutting soap bubbles into pieces.

Quantum field theory is one of the most successful and flexible tools physicists have ever developed, but it has its limits. Notably, the calculations involving strongly-coupled particles – particles like the gluons that "glue" quarks together inside protons and neutrons – are too difficult to perform. This leaves physicists in the unfortunate position of being unable to predict what happens when two gluons collide – they can't calculate the scattering amplitudes, to use the technical phrase.

The problem of gluons is so sticky that researchers study it in a simplified context known as N=4 Super Yang-Mills theory. Inside N=4, researchers can calculate what's likely to happen when gluons collide – can calculate the scattering amplitude – albeit not by using traditional techniques. Instead, they use a geometric shortcut made possible by string theory. At very strong couplings, each scattering amplitude is associated with a polygon.

This polygon technique was discovered in 2007. To use it, researchers count the number of incoming and outgoing particles, and consider a polygon with that number of sides. They then take that polygon and mentally build it out of wire and dip it in soap, as if to blow bubbles. The surface area of soap film is the scattering amplitude.

Unfortunately, up until now, this has only worked for maximally strong coupling, where the soap film is stretched taut. For other couplings, the soap film begins to vibrate quantum mechanically, which makes its area exponentially more difficult to calculate.

The Perimeter researchers were able to simplify this calculation. They broke the polygon up into four-sided pieces they called squares. They then studied the transitions between two adjacent squares, and found a way to add two squares together. Using this square-adding method over and over again, the researchers were able to sum over all possible surfaces. The result was a method that could calculate scattering amplitudes at any coupling strength.

This is technically known as solving scattering amplitudes for finite couplings, and has long been a stubborn and urgent problem in the field. This work lays the ground for a complete solution.

New Recipes for Quantum Field Theories

The recipe for solving most quantum field theories goes like this: start from something simple, add some complications, add some subtler complications, repeat until the complications get too small to matter, and declare the quantum field theory solved.

It sounds simple, but this recipe, technically known as perturbation theory, has helped develop quantum field theory, or QFT, into one of the most flexible and powerful tools physics has ever invented.

But what happens when perturbation theory breaks down?

It's not a hypothetical question. The basic recipe – start from the simple and add increasingly more subtle complications – works well in areas where the real-world complications are indeed small. But there are several major places where the complications aren't subtle, but overwhelmingly large, and where adding more complications does not slowly narrow in on a realistic answer, but instead produces predictions that are self-evidently nonsense.

The inability of QFT to handle the low-energy quarks and gluons – to answer the question of why quarks are normally confined inside protons and neutrons, for example – is the most famous example of a place where the perturbation recipe breaks down. Also in the non-perturbative regime are the physics of strongly interacting many-body systems, the physics inside black holes, and the physics of the very early universe.

No surprise, then, that the search for new recipes that will work in the non-perturbative regime is a major area of research. **Perimeter Faculty member Jaume Gomis** is hard at work cooking some up.

The way Gomis sees it, part of the problem in building non-perturbative QFTs is that we don't really understand the behaviour the theory is meant to explain. This leaves us trying to figure out a recipe for a dish without tasting the dish first.

Gomis uses powerful mathematical techniques in his quest to define the possible non-perturbative dynamics of QFTs. In particular, he is interested in dualities – places where two different theories, one perturbative and one non-perturbative, look very different, but turn out to be quantum mechanically equivalent. By exploiting these dualities, Gomis has been able to obtain some exact results in four-

dimensional QFTs for the first time. These results have yielded new insights into the non-perturbative dynamics of QFTs.

It's like the first taste of the dish – and it gives new hope for the development of new recipes.

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J. Gomis (Perimeter Institute) and S. Lee (Cambridge University), "Exact Kahler Potential from Gauge Theory and Mirror Symmetry," *JHEP* 1304 (2013) 019, arXiv:1210.6022.

Quantum Gravity

Quantum gravity is concerned with unifying Einstein's general theory of relativity and quantum theory into a single theoretical framework. Perimeter researchers are actively pursuing a number of approaches to this problem, including loop quantum gravity, spin foam models, asymptotic safety, emergent gravity, string theory, and causal set theory. The search for quantum gravity overlaps with other areas such as cosmology, particle physics, and the foundations of quantum theory.

The Left Hand of Gravity

Parity is the notion that if you do something – anything – then the version of that thing that you'd see when looking in a mirror should also be possible. It is only mostly true. Gravity looks the same when you look at it in a mirror. So does the strong force. So does electromagnetism. But the weak force does not.

As physicists work towards a theory that would unify all the forces – describing them as aspects of a single theory – the asymmetrical nature of the weak force is a problem. How can it be that this force, and only this force, can tell its right hand from its left?

Perimeter Faculty member Lee Smolin and his collaborators, Antonino Marciano and Stephon Alexander (both of Dartmouth), have addressed this issue in a new and surprising way. They propose a new unification of the weak and gravitational interactions that explains the asymmetry of the weak interactions under parity as due to a hidden asymmetry in the laws of gravity.

The idea does not come out of left field. Loop quantum gravity is a well-known approach to unifying gravity and the other interactions. Loop quantum gravity researchers often work with a reworking of general relativity known as the Plebanski reformulation. Like any reformulation, Plebanski is not a new theory – it does not describe new phenomenon or make new predictions – but a translation of an existing theory into a new mathematical language. Such reformulations often make theories, in this case the theory of general relativity, easier to work with, or show new ways in which they can be extended.

This is the case with Smolin's new work. The researchers show that an extended Plebanski theory would naturally unify gravity with the weak interactions in a way that explains the asymmetry of weak interactions. Roughly speaking, the gauge fields describing gravity and the weak interactions start off as mirror images of each other. But this symmetric world turns out to be unstable. As a result, the symmetry between left and right breaks spontaneously, which allows nature to find a stable point where the left and right halves of the fields behave very differently. One half becomes gravity and the other half the weak force.

Born, Again

Perimeter Faculty member Laurent Freidel and his collaborators are following an old trail and uncovering startling new ideas.

The trail begins in 1938, with Max Born – one of the fathers of quantum mechanics. Born was seeking, as generations of his scientific successors would, a unification between quantum mechanics and general relativity, because the two successful explanatory frameworks of the universe don't quite work together.

Born had noticed in quantum mechanics an intriguing symmetry between space and momentum – a principle that would become known as Born reciprocity – and he wondered if the elusive unification of quantum mechanics and general relativity might be achieved through a unification of space and momentum in some geometrical structure. Developing such a structure, however, proved too vexing for Born and for physicists who have attempted it in the seven decades hence.

But that may be about to change. Freidel and colleagues are trying to find a way to build that framework within the context of string theory.

"It's crazy enough that it might work," says Freidel. "It's a radical idea because it necessitates us to relax our notions of locality and question the existence of spacetime."

Radical, yes, but the ideas seem to work so far. Further research is required to check the ideas for consistency, "but it looks like the pieces are fitting together."

Freidel and collaborators have shown that Born reciprocity can naturally be implemented in string theory and showed that string theory predicts that spacetime and energy-momentum space will be curved. The researchers show how certain aspects of string theory impose a new mathematical structure on phase space, which they call a Born geometry. This Born geometry carries information about how spacetime is quantized.

The potential impact of this work is very high. It could lead to a radical refounding of string theory and will have deep consequences on our understanding of locality and the possible deviation from it. If true, the findings might even lead to the possibility of testing quantum gravity, with the hope of learning surprising new things about the nature of the universe.

It's speculative, theoretical work and Freidel is the first to admit there is "much more to be done," but says that the early results are tantalizing.

"All good ideas in physics come, they die, and they resurface again at the right time," he says. "I am heir to ideas about Born reciprocity, and I have to push it forward."

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Quantum Foundations

The study of quantum foundations concerns the conceptual and mathematical underpinnings of quantum theory. Research in quantum foundations at Perimeter Institute aims to refine and reformulate quantum theory in ways that express its true nature and structure. Research in this field is closely tied with work in quantum gravity and quantum information.

Assembly Instructions for a Universe

You can't build a car without knowing how all the pieces fit together.

The same goes for the universe. If you don't know how its many pieces combine to make the whole, good luck trying to figure out how it works.

Such is the simple and pragmatic idea behind recent fundamental work by **Perimeter Faculty member Lucien Hardy**. If we understand how the components of something are connected – in this case, the "something" in question could be spacetime itself – then we should gain a better understanding of the thing as a whole.

Like any other composite object, a region of spacetime is made up of smaller regions joined together. Hardy's paper, titled "On the theory of composition in physics," establishes a general theory of such combinations, as well as a common language with which these cosmic composites can be described.

With that groundwork established, Hardy proposes a principle – fittingly called the composition principle – stating that any calculations of physical properties in a composite object (like a car or a galaxy) should take the same form as the description of the object's composition.

What Hardy has outlined is a kind of rulebook – a set of guidelines for defining, describing, and making predictions about composite objects, from the imperceptibly tiny to the astronomically enormous.

This approach has already been applied to quantum theory and work is now under way to apply such composition ideas to general relativity. This kind of exploration will lead to valuable insights in the quest for a unified theory of quantum mechanics and general relativity – that is, the quest of quantum gravity research.

Given that Perimeter houses clusters of expertise in each of these areas – general relativity, quantum mechanics, quantum gravity, and related fields – the Institute itself is a kind of composite object. As such, sometimes the biggest discoveries come through probing the interconnectedness of its various parts.

A New Outlook on a Classic Law

Research by **Perimeter Faculty member Robert Spekkens**, for example, aims to bridge disparate areas of research, including information theories, resource theory, and thermodynamics.

In a recent example, Spekkens and collaborators have taken an old problem – how to properly formulate the Second Law of Thermodynamics – and looked at it through a new lens. The Second Law, in basic terms, states that a system will tend to become increasingly uniform – that temperature and heat and pressure are inclined to "even out."

But such definitions are fraught with questions and frequently the subject of debate. More than a half-century ago, Nobel laureate Percy Bridgeman succinctly summarized the problem: "There are almost as many formulations of the Second Law as there have been discussions of it."

Spekkens and collaborators decided to return to basic questions of thermodynamics, reframing them as a kind of "resource theory," inspired by fruitful work in quantum information research.

Techniques from quantum information theory are now helping us say new things about thermodynamics, explains Spekkens. In particular, a special kind of correlation that can hold between systems, known as "entanglement," has been studied extensively as the thing that powers various information-processing tasks, and results in this area inform the new work.

Information theory is relevant to thermodynamics because, roughly speaking, knowledge is power. Indeed, information can serve as "fuel" for doing useful work; just as it takes power to erase all the data from your hard drive, a wiped hard drive can serve as a battery from which power can be drawn.

Spekkens and collaborators (including former **Perimeter postdoc Markus Müller** and former **Perimeter Scholars International student Nicole Halpern**) examined how to quantify a state's deviation from "informational equilibrium" (i.e., a version of the "evened out" mode). They further discerned how that deviation can be put to use for mechanical and computational tasks, and how one state can be converted to another. The research examines various notions of state conversion and different scenarios in which it can arise.

The research not only provides new insight into how the Second Law can (and cannot) be formulated, it also forges new pathways between different areas of theoretical physics. It is the kind of research that creates new connective tissue between disparate disciplines and exemplifies the interdisciplinary approach to theoretical physics that Perimeter Institute was designed to foster.

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F.G. Brandao (University College London), M. Horodecki (University of Gdańsk), J. Oppenheim (University College London), J. Renes (ETH Zurich), and R.W. Spekkens (Perimeter Institute), “The resource theory of quantum states out of thermal equilibrium,” arXiv:1111.3882.

Honours, Awards, and Major Grants

- The Wilkinson Microwave Anisotropy Probe (WMAP) team, of which Faculty member Kendrick Smith is a member, was awarded the Gruber Prize.
- Director Neil Turok was awarded honorary doctorate degrees by Herriot-Watt University in Edinburgh and by the University of Guelph.
- Faculty member Davide Gaiotto was awarded a $100,000 New Horizons in Physics Prize by the Fundamental Physics Prize Foundation.
- Distinguished Visiting Research Chair Stephen Hawking was awarded a $3 million Fundamental Physics Prize by the Fundamental Physics Prize Foundation.
- Distinguished Visiting Research Chair S. James Gates Jr. was awarded the US National Medal of Science, the highest honour bestowed on scientists by the US government.
- Associate Faculty member Roger Melko was awarded the International Union of Pure and Applied Physics Young Scientist Prize in Computational Physics by the Council on Computational Physics.
- Associate Faculty member Roger Melko was named to the Canada Research Chair in Computational Quantum Many-Body Physics (Tier 2).
- Associate Faculty member Michele Mosca was named University Research Chair by the University of Waterloo, the university's highest distinction.
- Faculty member Daniel Gottesman and Senior Researcher Christopher Fuchs were both elected Fellows of the American Physical Society.
- Several Perimeter scientists were honoured with the Queen Elizabeth II Diamond Jubilee Medal for their achievements and contributions, as follows:
    - Director Neil Turok
    - Faculty member Robert Myers
    - Faculty member Lee Smolin
    - Associate Faculty member Raymond Laflamme
    - Associate Faculty member Michele Mosca
- Faculty member Robert Spekkens won first place in the Foundational Questions Institute (FQXi) essay contest; Postdoctoral Researcher Flavio Mercati was a fourth prize winner.
- Faculty member Luis Lehner was elected as a Fellow of the International Society for General Relativity and Gravitation.

- Postdoctoral Researcher Chad Hanna was elected co-chair of the Compact Binary Coalescence group of the international LIGO Scientific Collaboration (LSC).

- Associate Faculty member Sung-Sik Lee obtained a grant of $90,000 from the John Templeton Foundation.

- Faculty member Guifre Vidal and Associate Faculty member Roger Melko received a $450,000 grant from the John Templeton Foundation for their project, "Simulating Emergence in Quantum Matter."

- Associate Faculty member Michele Mosca and colleagues at the Institute for Quantum Computing were awarded $490,000 for the research project, "Facility for Global Quantum Communication and Security Certification," from the CFI Leading Edge Fund and the Ontario Research Fund (totalling $980,000).

- Perimeter scientists were awarded NSERC Discovery Grants totalling $1.79 million (over three- to five-year terms), including two Discovery Accelerator Supplements, as follows:
    - Faculty member Dmitry Abanin: $150,000 ($30,000/year over five years)
    - Faculty member Davide Gaiotto $386,000 ($53,200/year over five years, plus a Discovery Accelerator Supplement of $120,000)
    - Faculty member Natalia Toro: $260,000 ($52,000/year over five years)
    - Faculty member Xiao-Gang Wen: $545,000 ($85,000/year over five years, plus a Discovery Accelerator Supplement of $120,000)
    - Associate Faculty member Matthew Johnson: $162,000 ($27,000/year over five years, with an Early Career Researcher Supplement of $27,000)
    - Associate Faculty member Sung-Sik Lee: $125,000 ($25,000/year over five years)
    - Associate Faculty member Roger Melko: $165,000 ($33,000/year over five years)

Objective 2: To become the research home of a critical mass of the world's leading theoretical physicists

Summary of Achievements

- Re-appointed Director Neil Turok to a second five-year term, commencing in October 2013
- Named Neil Turok as the Mike and Ophelia Lazaridis Niels Bohr Chair in Theoretical Physics
- Appointed three full-time faculty members, bringing the total to 20
- Jointly appointed two associate faculty members, bringing the total to 12

Highlights

Director Re-appointed

- Re-appointed Neil Turok to a second five-year term as Institute Director

Since his arrival from the University of Cambridge in 2008, Neil Turok has led the Institute's strategic growth and development, helping Perimeter to grow rapidly in both size and international stature. Highlights of his first term include numerous recruitment successes,[5] the establishment of the Distinguished Visiting Research Chairs program, the creation of the Perimeter Scholars International (PSI) master's program, and the arrival of the first Perimeter Research Chairs, Xiao-Gang Wen and Davide Gaiotto. In March 2013, Perimeter's Board of Directors unanimously re-appointed Neil Turok to a second five-year term as director of the Institute, commencing in October 2013.

Perimeter Research Chairs

- Appointed Neil Turok as the third Perimeter Research Chair

The Perimeter Research Chairs program was designed to attract stellar, senior researchers to Perimeter and to Canada. Named for legendary scientists whose insights helped define modern physics, the program was designed to attract world-leading researchers in strategically chosen fields. Chairholders act as the nucleus of 'powerhouse' research groups able to make rapid progress on key problems. The Perimeter Research Chairs are envisioned as the most prestigious chairs in theoretical physics in the world, constituting a major talent gain for Canada.

[5] Over this period, Perimeter has recruited 12 new faculty and seven associate faculty.

In March 2013, Neil Turok was appointed as the Mike and Ophelia Lazaridis Niels Bohr Chair in Theoretical Physics. This is the third Perimeter Research Chair, in line with targeted objectives.[6] In addition to his leadership of Perimeter, Turok is a renowned scientific leader in the field of cosmology (see below).

New Perimeter Research Chair Appointment in 2012/13:

Neil Turok (PhD Imperial College London, 1983) was Professor of Physics at Princeton University and Chair of Mathematical Physics at the University of Cambridge before assuming his current position as Director of Perimeter Institute. Turok's research focuses on developing fundamental theories of cosmology and new observational tests. His predictions for the correlations of the polarization and temperature of the cosmic background radiation (CBR) and of the galaxy-CBR correlations induced by dark energy were recently confirmed. With Stephen Hawking, he discovered instanton solutions describing the birth of inflationary universes. His work on open inflation forms the basis of the widely discussed multiverse paradigm. With Paul Steinhardt, he developed an alternative, cyclic model for cosmology, whose predictions are so far in agreement with all observational tests. Among his many honours, Turok was awarded Sloan and Packard Fellowships and the James Clerk Maxwell medal of the Institute of Physics (UK). He is a Canadian Institute for Advanced Research (CIFAR) Fellow in Cosmology and Gravity and a Senior Fellow of Massey College in the University of Toronto. In 2012, Turok delivered the CBC Massey Lectures. The lectures were published as *The Universe Within*, a bestseller which won the 2013 Lane Anderson Award, Canada's top prize for popular science writing. Born in South Africa, Turok founded the African Institute for Mathematical Sciences (AIMS) in Cape Town in 2003. AIMS has since expanded to a network of four centres – in South Africa, Senegal, Ghana, and Cameroon – and has become Africa's most renowned institution for postgraduate training in mathematical science. For his scientific discoveries and his work founding and developing AIMS, Turok was awarded a TED Prize in 2008. He has also been recognized with awards from the World Summit on Innovation and Entrepreneurship (WSIE) and the World Innovation Summit on Education (WISE).

Faculty

- Appointed three full-time faculty members – Dmitry Abanin, Luis Lehner, and Kendrick Smith – bringing the total to 20

In fall 2012, Perimeter Institute welcomed two outstanding junior faculty members, Dmitry Abanin and Kendrick Smith. In addition, after three years as an associate faculty member with the University of Guelph, Luis Lehner was appointed to a senior faculty position at Perimeter in September 2012. This brings the Institute's full-time faculty to 20, exceeding targeted objectives.

[6] The first two Perimeter Research Chairs were Xiao-Gang Wen as the BMO Financial Group Isaac Newton Chair in Theoretical Physics in 2011 and Davide Gaiotto as the Galileo Galilei Chair in Theoretical Physics in 2012.

New Faculty Appointments in 2012/13:

Dmitry Abanin (PhD Massachusetts Institute of Technology, 2008) joined Perimeter in fall 2012, after holding postdoctoral positions at the Princeton Center for Theoretical Science (2008-11) and Harvard University (2011-12). A leading young condensed matter theorist, Abanin's research has focused on developing a theoretical understanding of Dirac materials, focusing on quantum transport of charge and spin, and finding new ways of controlling their electronic properties. Some of his theoretical work has been experimentally confirmed by groups at the Max Planck Institute, University of Manchester, University of California, Riverside, Harvard University, Columbia University, and elsewhere.

Luis Lehner (PhD University of Pittsburgh, 1998) began an associate faculty appointment with Perimeter and the University of Guelph in 2009 and joined Perimeter's full-time faculty in September 2012. He previously held postdoctoral fellowships at the University of Texas at Austin and the University of British Columbia, and he was a member of Louisiana State University's faculty from 2002 to 2009. Lehner's many honours include the Honor Prize from the National University of Cordoba, Argentina, a Mellon pre-doctoral fellowship, the CGS/UMI outstanding dissertation award, and the Nicholas Metropolis award. He has been a PIMS fellow, a CITA National Fellow, and a Sloan Research Fellow, and he is currently a Fellow of the Canadian Institute for Advanced Research (CIFAR) in the Cosmology and Gravity program, the Institute of Physics, and the American Physical Society.

Kendrick Smith (PhD University of Chicago, 2007) joined Perimeter in fall 2012,[7] following postdoctoral fellowships at the University of Cambridge (2007-09) and Princeton University (2009-12). He is a cosmologist, with a foot in the worlds of both theory and observation. Smith is a member of several experimental teams, including the WMAP collaboration, which won the 2012 Gruber Cosmology Prize, as well as QUIET and the Planck collaboration. He has achieved several landmark results, including the first detection of gravitational lensing in the cosmic microwave background (CMB) radiation.

Associate Faculty

- Appointed two new associate faculty members, bringing the total to 12

Through its associate faculty program, Perimeter recruits top scientific talent in partnership with top Canadian universities, spreading the resulting "brain gain" and contributing to Canada's growing strength in fundamental physics. Associates spend up to 50 percent of their time at Perimeter, in addition to teaching and conducting research at the partner university.

[7] Smith was granted a one-year leave of absence to participate in the Hyper-Suprime Cam (HSC) project on the Hawaii-based Subaru telescope, after which he will bring full data rights to Perimeter. He is also expected to lead the Institute's participation in the Large Synaptic Survey Telescope (LSST), which will follow the HSC and lead to unprecedented tests of dark energy and other signals of primordial physics. He will be on-site at Perimeter starting in September 2013.

Luis Lehner provides an instructive example of the strategic value of the associate faculty program. In 2009, he was recruited from Louisiana State University via a joint appointment between Perimeter and the University of Guelph. In 2012, Lehner joined Perimeter's senior faculty full time (see above), and the Institute initiated a search for another associate with Guelph. The net result is growing regional strength in the related areas of gravitational physics, astrophysics, and computational physics. This has in turn helped both Guelph and Perimeter attract several outstanding junior faculty, postdoctoral researchers, and graduate students.

In 2012/13, in line with targeted objectives, Perimeter appointed two new associate faculty members, cosmologist Matthew Johnson (with York University) and condensed matter theorist Roger Melko (at the University of Waterloo). The Institute now has 12 associate faculty,[8] and new searches are under development with the University of Guelph, Queen's University, the University of Toronto, the University of Waterloo, and Western University.

New Associate Faculty Appointments in 2012/13:

Matthew Johnson (PhD University of California, Santa Cruz, 2007) joined Perimeter's faculty in August 2012, jointly appointed with York University. He previously held postdoctoral positions at the California Institute of Technology (2007-10) and Perimeter (2010-12). Johnson is a cosmologist whose interdisciplinary research seeks to understand how the universe began, how it evolved, and where it is headed. To this end, he designs data analysis algorithms to confront fundamental theory with observations of the cosmic microwave background radiation.

Roger Melko (PhD University of California, Santa Barbara, 2005) joined Perimeter's faculty in September 2012, jointly appointed with the University of Waterloo, where he has been since 2007. Melko is a condensed matter theorist who develops new computational methods and algorithms to study strongly correlated many-body systems, focusing on emergent phenomena, ground state phases, phase transitions, quantum criticality, and entanglement. He was a Wigner Fellow at Oak Ridge National Laboratory from 2005 to 2007 and received an Early Researcher Award in 2010.

[8] Associate faculty are appointed for fixed terms ranging from three to seven years. In the last year, Adrian Kent and Luis Lehner completed their terms. Lehner joined Perimeter's full-time faculty, while Kent accepted a Distinguished Visiting Research Chair position with the Institute.

Objective 3: To generate a flow-through of the most promising talent

Summary of Achievements

- Hired 20 postdoctoral researchers in 2012/13 and recruited an additional 18 for 2013/14
- Six departing postdoctoral researchers obtained tenure-track faculty positions
- Trained 29 students from 15 countries, including 10 women, through the Perimeter Scholars International (PSI) master's program, as well as 39 PhD students
- Hosted 19 Visiting Graduate Fellows for a total of 22 visits
- Provided research training to seven undergraduate students

Highlights

Postdoctoral Researchers

- Twenty postdoctoral researchers were appointed in 2012/13
- Six departing postdoctoral researchers obtained tenure-track faculty positions

In 2012/13, Perimeter appointed 20 postdoctoral researchers and recruited an additional 18 for 2013/14, exceeding targeted outcomes.[9]

Perimeter is known internationally for its exceptionally supportive and stimulating environment, in which postdocs have full research independence and are encouraged to pursue novel, ambitious lines of research.[10] The Institute offers collaboration opportunities second to none through numerous strategic partnerships, including agreements with observational and experimental centres like TRIUMF, CERN, and the Institute for Quantum Computing at the University of Waterloo (see Objective 6). Perimeter also leverages its partnerships to offer joint postdoctoral positions to some top candidates.[11]

Training at Perimeter pays off. In 2012/13, despite an academic market that remains extremely competitive worldwide, six departing postdoctoral researchers obtained tenure-track faculty positions: Eric Chitambar (Southern Illinois University), Sarah Croke (University of Glasgow), Adrienne Erickcek (University of North Carolina), Simone Giombi (Princeton University), Leonardo Modesto (Fudan University, China) and David Skinner (University of Cambridge). Other departing postdocs obtained continuing academic positions at international institutions, including the University of New Brunswick,

[9] Resident researchers' success in obtaining grant funding enabled the Institute to hire more postdoctoral researchers than projected.

[10] Perimeter received 694 applications for the 2013/14 positions, the largest applicant pool to date, attesting to the Institute's excellent reputation.

[11] In 2012/13, Perimeter offered four such positions – three with the Institute for Quantum Computing and one with the Institute for Advanced Study in Princeton.

Harvard University, Pennsylvania State University, the University of Paris XIII, and the German Electron Synchrotron (DESY); some also obtained positions in industry, including as a Risk Analyst for CitiBank.

Perimeter Scholars International (PSI)

- PSI trained 29 students, including 10 women, from 15 countries in 2012/13

PSI is a master's level program that attracts highly talented university graduates from around the world, bringing them to the cutting edge of theoretical physics in one academic year. The innovative curriculum features three-week course modules taught by some of the world's top lecturers.[12] Six postdoctoral-level PSI Fellows and several graduate teaching assistants provide students with tutorial support throughout the year.[13] A master's degree is conferred by the University of Waterloo on completion of the program.

Admission to PSI is highly competitive, with applications from 62 countries and an overall acceptance rate of 8.9 percent.[14] The resulting quality of students is extremely high; many members of the 2013/14 class hold competitive scholarships, including five from NSERC and two from CERN. PSI also strengthens Perimeter's ties to regional partners – including the University of Waterloo, McMaster University, and TRIUMF, whose faculty teach PSI courses and supervise research projects. In addition, 10 PSI courses were opened to non-Perimeter graduate students (with special permission), enriching course offerings for students throughout the region.[15]

PSI continues to fulfill its mandate of attracting graduates with high scientific potential to Canada and retaining the best among them for continued doctoral training. Eleven of the 2012/13 graduates are pursuing their PhDs in Canada, seven of them at Perimeter. Most of the others have gone on to PhD programs at top international institutions, including the California Institute of Technology, University of Cambridge, Massachusetts Institute of Technology, and University of Oxford.

[12] In 2012/13, the PSI faculty comprised 12 Perimeter faculty members, one Distinguished Visiting Research Chair, and 10 other international scientists

[13] Being a PSI Fellow in turn provides valuable teaching experience; this year, PSI Fellow Sarah Croke obtained a tenure-track position at the University of Glasgow.

[14] For 2013/14, 31 students from 17 countries, including 10 women, have been accepted from among 349 applicants from 62 countries. Two members of the newest class are graduates of the African Institute for Mathematical Sciences (AIMS), Perimeter's global outreach partner.

[15] Twenty students from surrounding universities enrolled in PSI courses.

PhD Students

- 39 PhD students were in residence at Perimeter in 2012/13
- Six PhD students supervised by Perimeter faculty graduated from partner universities
- Two graduates founded new companies in Canada

The PhD program continues to grow as planned, as the Institute recruits top PSI graduates for continued studies with Perimeter faculty. At year's end, Perimeter had 39 students in residence, 21 of whom had received their master's degree through the PSI program. Since Perimeter is not a degree-granting institution, the PhD program brings top students not only to Perimeter, but also to the partner universities where they receive their degrees, constituting a significant talent gain for Canada.

Notably, of this year's six graduates, two founded Canadian start-up companies (the remainder obtained competitive postdoctoral positions at international institutions). Jorge Escobedo is putting his mathematical modelling skills to use as the Co-Founder and Chief Technology Officer of Toronto-based **Canopy Labs**, helping businesses predict consumer behaviour and target sales through data analysis. Cozmin Ududec is the Co-Founder and Risk Management Lead of Winnipeg-based **Invenia Technical Computing**, responsible for quantifying and managing financial risk in energy arbitrage markets.

Visiting Graduate Fellows

- Perimeter hosted 19 Visiting Graduate Fellows for a total of 22 visits in 2012/13, with stays ranging from one to eight months.

The Visiting Graduate Fellows program brings advanced PhD students from around the world to spend several months at the Institute, enabling them to join Perimeter's research community and interact with leading researchers at a pivotal time in their research training. In its first full year of operation, the program has already nearly achieved its steady state goal of hosting six to eight Visiting Graduate Fellows at any given time.

Undergraduate Students

- Perimeter provided research training to seven exceptional undergraduates from top institutions

The Undergraduate Student program exposes promising undergraduates to high-level research through two- to four-month projects, while giving Perimeter's postdoctoral researchers valuable mentoring experience. The program also acts as a means of attracting talent to the Institute – for example, Emily Adlam came from the University of Oxford to complete a summer project in 2012 and has returned to Perimeter as a member of the 2013/14 PSI class.

Objective 4: To become the second research home for many of the world's outstanding theorists

Summary of Achievements

- Appointed 12 leading scientists as Distinguished Visiting Research Chairs, bringing the total to 34
- Welcomed four accomplished young researchers as Visiting Fellows, bringing the total to 10
- Hosted 432 visiting scientists for a total of 462 scientific visits

Highlights

Distinguished Visiting Research Chairs

- Appointed 12 new DVRCs and renewed six more, bringing the total to 34[16]
- 15 DVRCs made 29 visits in 2012/13

Perimeter's unique Distinguished Visiting Research Chairs (DVRC) program is both strategic and cost-effective. DVRCs are leading scientists who visit Perimeter for extended periods to do research, collaborate, and participate in all facets of life at Perimeter. They are appointed for renewable, three-year terms, while retaining permanent positions at their home institutions. These luminaries – including Stephen Hawking, Nima Arkani-Hamed, Leonard Susskind, and Nobel laureate Gerard 't Hooft – collectively span an enormous range of expertise (see Appendix C: Distinguished Visiting Research Chairs).

For DVRCs, time spent at Perimeter is highly productive, since they are freed from usual administrative and teaching duties. In turn, their presence as collaborators, conference speakers, PSI lecturers, and Public Lecture speakers greatly enhances and inspires Perimeter's resident community.

Perimeter's DVRCs continue to be recognized at the highest levels. In 2012/13, Hawking was awarded one of two $3 million Special Fundamental Physics Prizes, while S. James Gates Jr. received the National Medal of Science from President Barack Obama, the highest honour bestowed on scientists by the US government.

New Distinguished Visiting Research Chair Appointments in 2012/13:

Matthew Fisher (PhD University of Illinois at Urbana-Champaign, 1986) 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

[16] The six DVRCs whose terms were renewed through 2015 are Patrick Hayden, Leo Kadanoff, Sandu Popescu, Paul Steinhardt, William Unruh, and Mark Wise.

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. He has over 160 publications.

Alexander Goncharov (PhD Institute of Mathematics, Novosibirsk, 1987) is a Professor in the Department of Mathematics at Yale University. Prior to joining Yale's faculty, he was a professor at Brown University, the Max Planck Institute for Mathematics, and the Massachusetts Institute of Technology. Goncharov's research primarily concerns mathematical physics, including arithmetic algebraic geometry and representation theory. He is known for the Goncharov conjecture, which suggests that the cohomology of certain motivic complexes coincides with pieces of K-groups. In 1992, Goncharov won the European Mathematical Society Prize.

F. Duncan M. Haldane (PhD University of Cambridge, 1978) is the Eugene Higgins Professor of Physics at Princeton University. His research explores strongly interacting quantum many-body condensed matter systems using non-perturbative 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 (PhD University of Texas at Austin, 1983) 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*.

Adrian Kent (PhD Cambridge, 1996) is a Reader in Quantum Physics with the University of Cambridge. He has previously held positions as an Enrico Fermi Postdoctoral Fellow at the University of Chicago, a member of the Institute for Advanced Study, and a Royal Society University Research Fellow at the University of Cambridge. Prior to becoming a DVRC, Kent was an associate faculty member at Perimeter Institute. His research focuses on the foundations of physics, quantum cryptography, and quantum information theory, including the physics of decoherence, novel tests of quantum theory and alternative theories, and new applications of quantum information.

Ramesh Narayan (PhD Bangalore University, 1979) is the Thomas Dudley Cabot Professor of the Natural Sciences at Harvard University. He is an astrophysicist who has won international renown for his research on black holes. Narayan has also carried out research in a number of other areas of theoretical astrophysics, including accretion disks, gravitational lensing, gamma-ray bursts, and neutron stars. He is

a Fellow of the Royal Society of London and the American Association for the Advancement of Science, and a member of the International Astronomical Union and the American Astronomical Society.

Peter Shor (PhD Massachusetts Institute of Technology, 1985) 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 (PhD Institute for Nuclear Research – Moscow, 1995) 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 (PhD Massachusetts Institute of Technology, 1982) 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.

Raman Sundrum (PhD Yale University, 1990) 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 (PhD University of California, San Diego, 1993) 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.

Steven White (PhD Cornell University, 1988) is a Professor in the Department of Physics at the University of California, Irvine. His primary research concerns condensed matter theory with an emphasis on numerical approaches for strongly correlated magnetic and superconducting systems. In 1992, White invented the density matrix renormalization group (DMRG), a numerical variation technique for high accuracy calculations of the low energy physics of quantum many body systems. For his efforts, White has been recognized as a Fellow of the American Physical Society (1998) and the American Association for the Advancement of Science (2008). In 2003, he won the Aneesur Rahman Prize, the highest honour in the field of computational physics given by the American Physical Society.

Visiting Fellows

- Four new Visiting Fellows were appointed in 2012/13
- Eight Visiting Fellows made a total of 13 visits

Since it was created in 2011, the Visiting Fellows program has quickly become an important tool for bringing accomplished researchers to Perimeter on a regular basis. Following the blueprint of the DVRC program, Visiting Fellows span a wide range of expertise, are appointed to renewable terms, and retain their positions at other institutions while coming to Perimeter for extended research visits.

With this year's appointments, Perimeter has achieved the program's steady state goal of 10. Three of this year's appointees are outgoing Perimeter postdoctoral researchers, with whom the Institute can retain a relationship while strengthening ties to their new home institutions.

New Visiting Fellow Appointments in 2012/13:

Fernando Brandão (PhD Imperial College London, 2008) is a Lecturer at University College London. His research concerns quantum information, quantum computing, and quantum optics, particularly their interplay with mathematics and computer science in understanding the possibilities and limitations of quantum mechanical systems. Among his honours, Brandão won the Quantum Electronics Division PhD Thesis Prize of the Institute of Physics (2008), the Quantum Electronics and Optics Division Prize of the European Physical Society (2009), and a QIPC European Quantum Information Young Investigator Award (2013).

Giulio Chiribella (PhD University of Pavia, 2006) is an Associate Professor at the Institute for Interdisciplinary Information Sciences at Tsinghua University in China. His research interests lie in quantum information theory, quantum foundations, and mathematical physics – particularly at the intersection of these fields. In 2010, Chiribella won the Hermann Weyl Prize for his work on the application of group theoretical models to the problem of quantum estimation of states and processes.

Razvan Gurau (PhD University of Paris, 2007) is a Researcher at the Theoretical Physics Center at École Polytechnique in France. His research interests lie in mathematical physics, particularly in both perturbative and non-perturbative aspects of the renormalization of quantum field theories. His work is relevant for physics problems ranging from quantum gravity to condensed matter. For his work in quantum gravity, Gurau won the Hermann Weyl Prize for 2012.

David Skinner (PhD University of Oxford, 2003) is a tenure-track Lecturer at the University of Cambridge. Skinner is interested in mathematical aspects of quantum field theories, particularly their overlap with twistor theory and string theory. His recent work explores the rich geometric structures present in the scattering amplitudes of four-dimensional gauge theory.

Visitor Program

- In 2012/13, Perimeter hosted 432 visiting scientists for a total of 462 scientific visits, including 392 short-term scientific visitors, 15 Distinguished Visiting Research Chairs, and eight Visiting Fellows[17]
- 17 long-term Visiting Researchers came to work at Perimeter during leaves (e.g., sabbaticals) from their home institutions

Perimeter Institute's active visitor program enables its resident scientists to stay abreast of recent developments, exchange ideas, and spark new collaborations. Visiting researchers, meanwhile, benefit from having the time and space for the intense, sustained work required to tackle tough problems. The program is also a recruitment aid, showcasing Perimeter's vibrant research environment and the excellent administrative support that enable scientists to maximize productivity. In the past year, many visits have led to new appointments, including Zheng-Cheng Gu as the Institute's first Director's Fellow.

[17] These 15 DVRCs accounted for 29 visits, while the eight Visiting Fellows made a total of 13 visits.

Objective 5: To act as a hub for a network of theoretical physics and math centres around the world

Summary of Achievements

- Renewed two existing institutional partnerships and formed three new ones
- Created a joint postdoctoral fellowship with the Fields Institute for Research in Mathematical Science at the University of Toronto
- Partnered on six joint workshops and conferences held at Perimeter and sponsored an additional 10 off-site workshops and conferences
- Provided expertise to the African Institute for Mathematical Sciences – Next Einstein Initiative (AIMS-NEI), which doubled its network from two to four centres over the last year

Highlights

Collaborations and Partnerships

Perimeter's institutional partnerships with leading institutes in Canada and abroad provide scientific collaboration and training opportunities, enabling it to act as a global research hub. In 2012/13, the Institute signed three new partnerships and renewed existing agreements with the Centre for Theoretical Cosmology (CTC) at the University of Cambridge and TRIUMF, Canada's national laboratory for particle and nuclear physics, in line with targeted objectives.

New Partnerships, 2012/13:

Tri-Institute Summer School on Elementary Particles (TRISEP)

Perimeter has partnered with fellow Canadian institutes TRIUMF and SNOLAB[18] to convene a new international summer school for graduate students and postdoctoral researchers on hot topics in particle physics. The first Tri-Institute Summer School on Elementary Particles (TRISEP) took place at TRIUMF in July 2013, featuring leading particle physicists lecturing on collider physics, neutrino physics, dark matter, Monte Carlo techniques, and physics beyond the Standard Model. Further summer schools are planned for 2014 and 2015, hosted by SNOLAB and Perimeter respectively.

[18] TRIUMF (located in Vancouver, BC) is Canada's national laboratory for particle and nuclear physics, and SNOLAB (located in Sudbury, ON) is an underground science laboratory specializing in neutrino and dark matter physics.

Weizmann Institute of Science

Like Perimeter, the Weizmann Institute of Science in Rehovot, Israel, is a multidisciplinary research institution seeking to improve our understanding of nature. The two institutes have signed a three-year agreement to facilitate research visits and promote scientific collaboration between their researchers, as well encouraging collaboration on outreach programming, an area of focus at both institutes. Weizmann's Faculty of Physics includes both theorists and experimental scientists, giving interested Perimeter researchers another link to experimental physics.

International School for Advanced Studies (SISSA)

The International School for Advanced Studies (SISSA) is a scientific centre of excellence located in Trieste, Italy. Its three main research areas are physics, mathematics, and neuroscience, and many of its researchers are experts in fields of interest to Perimeter scientists. As such, Perimeter and SISSA have signed an agreement to facilitate scientific visits and promote collaborations between researchers in areas of common interest. The agreement also encourages collaboration between the two institutes on outreach programs.

In addition to these formal collaboration agreements, Perimeter pursued informal partnerships that benefitted the international physics community. Some of these highlights from 2012/13 include:

- **"LHC Search Strategies"** (August 2-4, 2012): This invitation-only workshop brought together theorists from Perimeter and other leading institutions with experimentalists from the Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider at CERN to analyze lessons learned from the Higgs boson search and plan future directions. Steve Worm, one of the leaders of CMS, said of the gathering, "Discussions at PI have contributed to an ongoing strategic shift in the management and intellectual direction taken by the collaboration. Within my group, the PI workshop is seen as a turning point in our strategic development, and the discussions we enjoyed there should seed changes which will have a large impact on our future work."

- **Fields-Perimeter Africa Fellowship:** The Fields Institute for Research in Mathematical Sciences at the University of Toronto and Perimeter formed a partnership to fund four one-year joint postdoctoral fellowships. The positions are intended for African nationals who have recently acquired their PhD and whose research interests lie in the mathematical sciences or fundamental theoretical physics. Fellows will be encouraged to spend time at both institutes, with the emphasis depending on their research interests. The first fellowship recipient is expected to arrive in the fall of 2013.

- **"Cosmological Frontiers in Fundamental Physics 2013"** (July 8-11, 2013): The seventh in a series of conferences jointly organized with the International Solvay Institutes in Brussels, Belgium, and the AstroParticle and Cosmology (APC) laboratory at the University of Paris VII, this conference brought together 80 scientists to discuss the implications of the cosmic microwave

background data from the Planck satellite, which was made public just weeks before the meeting, and recent developments in massive gravity.

Lastly, Perimeter hosted several important international conferences[19] in 2012/13 and jointly sponsored 10 workshops and conferences with national and international partners.[20]

Global Outreach

Perimeter's Global Outreach initiative shares expertise (not funding) to assist in the growth of scientific centres of excellence around the world. The current focus of these efforts is the African Institute for Mathematical Sciences – Next Einstein Initiative (AIMS-NEI), a pan-African project founded by Perimeter Director Neil Turok in 2003 to establish a network of centres providing advanced mathematical and scientific training to exceptional African graduates.

AIMS-NEI has become a flourishing pan-African network. In August 2012, the third centre opened in Ghana, and AIMS-Cameroon is expected to open in fall 2013. Perimeter continued to provide relevant expertise in 2012/13. Examples include the following:

- Several Perimeter researchers taught at AIMS centres
- Perimeter staff provided organizational planning and management expertise in planning the launch of AIMS-Ghana
- Assisted AIMS in obtaining new funding, including a $29 million from the UK Department of International Development and "One for Many" scholarship support from the Fields Institute
- Helped AIMS-NEI forge a partnership with Communitech, a regional tech start-up support organization, to provide an internship for a recent AIMS graduate
- Provided office space to AIMS-NEI's Director of Advancement for North America

[19] These include "Applications of Jet Substructure to New Physics Searches" (February 21-23, 2013) with TRIUMF, and "The Quantum Landscape" (May 27-31, 2013) with the Foundational Questions Institute, the Institute for Quantum Computing, and the Rotman Institute of Philosophy.

[20] Partners have included the International Centre for Theoretical Physics – South American Institute for Fundamental Research and TRIUMF, Canada's national laboratory for particle and nuclear physics.

Objective 6: To increase Perimeter's role as Canada's focal point for foundational physics research

Summary of Achievements

- Renewed 12 Affiliate members across the country, giving the Institute 117 Affiliates in total
- Strengthened ties to regional, national, and international experimental centres
- Fostered the emerging "Quantum Valley" ecosystem
- Conducted joint faculty searches with the University of Waterloo and York University, resulting in the appointment of two new associate faculty members (see Objective 2)
- Partnered with the University of Waterloo to deliver the PSI master's program and involved faculty from Canadian institutions as lecturers[21] (see Objective 3)
- Hosted six joint workshops and conferences with national and international partners, and sponsored an additional 10 (see Objective 7)

Highlights

Perimeter is a hub of theoretical physics research in Canada. In 2012/13, the Institute continued to provide unique resources to the national scientific community through courses, seminars, workshops, and conferences (see Objective 7). It brought top talent to Canada at all levels, from the students coming to Perimeter through the PSI master's program (see Objective 3) to the joint recruitment of postdoctoral researchers (see Objective 3) and associate faculty (see Objective 2). Perimeter continues to cultivate strategic partnerships across the country through its Affiliate member program, engagement with experimental centres, and the fostering of the new "Quantum Valley" in Waterloo Region (see below).

Affiliate Members

- Perimeter has 117 Affiliate Members from research institutions across Canada

Perimeter's Affiliate member program has long been a crucial means of ensuring the Institute is a focal point for foundational physics research in Canada. Affiliates are select researchers at universities across the country who are invited to Perimeter for regular informal visits. Affiliates gain access to an active community of researchers spanning the entire spectrum of physics, allowing them to explore ideas they might not necessarily be exposed to at their home institutions. Meanwhile, Perimeter strengthens its connections with more than 25 of Canada's top research centres and provides its resident scientists with new collaboration opportunities. The result is a net gain for Canada's entire physics community.

[21] These included Andrew Childs (University of Waterloo), Joseph Emerson (University of Waterloo/Institute for Quantum Computing), and David Morrissey (TRIUMF).

In 2012/13, Perimeter renewed the terms of 12 Affiliates through 2015, ensuring this vibrant community of scientists will continue to enrich the Institute's research environment. Perimeter currently has 117 Affiliates, in line with targeted objectives (see Appendix D: Affiliate Members).

Engagement with Experimental Centres

Experiment is the ultimate test of all theory. For this reason, Perimeter continued to expand and deepen its many ties to experimental centres.

Perimeter's primary experimental partner is the Institute for Quantum Computing (IQC) at the University of Waterloo, which it helped launch in 2002. Research at the two institutes is highly complementary, and research ties have continued to grow. Many Perimeter researchers are cross-appointed at IQC;[22] last year, for example, Perimeter and IQC co-recruited three postdoctoral researchers (see Objective 3).[23] Many more are linked through informal ties, and there are numerous graduate students doing research at both institutions.

In 2012/13, Perimeter also renewed its partnership with TRIUMF, Canada's national laboratory for particle and nuclear physics, and launched the Tri-Institute Summer School on Elementary Particles (TRISEP) with TRIUMF and SNOLAB, an underground science laboratory specializing in neutrino and dark matter physics (see Objective 5).

Through strategic recruitment, Perimeter participates in some of the most important experiments in physics and has data rights to their results. Faculty member Kendrick Smith, for example, has ties to the Hyper-Suprime Cam (HSC) project at the Subaru telescope, as well as to the Planck, WMAP, and QUIET collaborations (see Objective 2). Perimeter has also become an international partner in the Large Synaptic Survey Telescope (LSST) collaboration, which Smith is expected to join as a participating scientist.

In particle physics, faculty members Philip Schuster and Natalia Toro continue to increase ties between Perimeter theorists and experimentalists at the Large Hadron Collider; the "LHC Search Strategies" workshop held at Perimeter in August 2012 was described as a "turning point" in the LHC collaboration's strategic development by one of its leaders (see Objective 5).

[22] Perimeter Associate Faculty members Raymond Laflamme (IQC's Director), Michele Mosca (IQC Deputy Director), and David Cory are all jointly appointed at IQC. Perimeter researchers who are also IQC Affiliates include: Faculty members Guifre Vidal, Robert Spekkens, Daniel Gottesman, and Lucien Hardy, Associate Faculty member Roger Melko, Distinguished Visiting Research Chair Adrian Kent, and postdoctoral researchers Hector Bombin, Oliver Buerschaper, Lukasz Cincio, Sarah Croke, Alioscia Hamma, Robert Pfeifer, and Huangjun Zhu.

[23] Gus Gutoski, Zlatko Papić, and Huan Yang were each hired for three-year postdoctoral positions jointly between Perimeter Institute and the Institute for Quantum Computing.

Fostering Quantum Valley

Quantum information processing, or quantum computing, is one of the fastest moving fields in science, seeing rapid progress from theory to prototype components and devices. It is now widely believed that quantum technologies will transform society much as the first wave of classical computers did.

Perimeter researchers do crucial theoretical work that underpins the entire field, working closely with experimentalists at IQC. Many of the field's pioneers are located at one or both of these centres. The surrounding academic community (including the Quantum-Nano Centre, the Waterloo Institute of Nanotechnology, and the University of Waterloo), an innovative and vibrant start-up community, and the presence of venture capital (including Mike Lazaridis' latest venture, Quantum Valley Investments) all combine to create an ecosystem primed to develop and commercialize breakthroughs. There is thus good reason to believe that Waterloo Region possesses the infrastructure and leading minds to become the next Silicon Valley – or "Quantum Valley."

Perimeter seeded this emerging ecosystem and continues to work strategically with partners to realize this rare opportunity for Canada. In the last year, for example, recruitment has emphasized quantum specialists like Faculty members Dmitry Abanin and Roger Melko (see Objective 2); DVRCs Peter Shor, Steven White, Matthew Fisher, Duncan Haldane, and Zhenghan Wang (see Objective 4); and numerous postdoctoral researchers. Perimeter Director Neil Turok and Associate Faculty members David Cory and Raymond Laflamme now sit on the Scientific Advisory Committee for Quantum Valley Investments.

Together with other key players in Waterloo Region, Perimeter is working to ensure Canada remains at the forefront of the international race to create new quantum industries, which will in turn spark major job and value creation.

Objective 7: To host timely, focused conferences, workshops, seminars, and courses

Summary of Achievements

- Held 10 timely, focused conferences and workshops, attended by nearly 700 scientists from around the world
- Partnered on six joint workshops and conferences held at Perimeter and sponsored an additional 10 off-site workshops and conferences (see Objective 6)
- Presented 301 scientific talks (257 seminars and 44 colloquia)
- Delivered three courses to researchers and students from surrounding universities

Highlights

Conferences and Workshops

- Held 10 focused conferences and workshops, including one with over 100 participants, meeting targeted objectives.[24]

Perimeter has built an internationally renowned conference program by selecting topics with high potential for stimulating significant outcomes. This year, 697 scientists attended Institute conferences and workshops, demonstrating its role as a major node of exchange for theoretical physics. The conference program also strengthens Perimeter's ties to institutional partners; this year, the Institute partnered on six workshops and conferences with national and international partners[25] and sponsored an additional 10 off-site scientific gatherings.[26]

[24] "Loops 13" (July 22-26, 2013) featured 194 attendees, including DVRCs Renate Loll and William Unruh and Visiting Fellows Razvan Gurau, Etera Livine, Vincent Rivasseau, and David Skinner.

[25] These included: (1) "LHC Search Strategies," with CERN; (2) "Applications of Jet Substructure to New Physics Searches," with TRIUMF; (3) "Women and Physics: Past, Present, and Future," with the University of Waterloo and Wilfrid Laurier University; (4) "The Quantum Landscape," with the Foundational Questions Institute, Institute for Quantum Computing, and Rotman Institute of Philosophy; (5) "Cosmological Frontiers in Fundamental Physics 2013," with the Templeton Foundation, the International Solvay Institutes, and the AstroParticle and Cosmology laboratory at the University of Paris VII; and (6) "Loops 13," with the Templeton Foundation and University of Waterloo.

[26] These included: (1) "Symbolic Computation in Theoretical Physics: Integrability and Super-Yang Mills," International Centre for Theoretical Physics – South American Institute for Fundamental Research; (2) "Lake Louise Winter Institute," University of Alberta; (3) "Black Holes 9," University of Saskatchewan; (4) "8th Conference on Theory of Quantum Computation, Communication, and Cryptography," University of Guelph; (5) "Theory Canada 8," Bishop's University; (6) "Complex Quantum Networks," Institute for Quantum Computing; (7) "GAP 2013," Mathematical Research Centre (CRM) at the University of Montreal; (8) "13th Canadian Summer School on

Highlights of the last year included:

- **"LHC Search Strategies"** (August 2-4, 2012): Weeks after teams at the Large Hadron Collider (LHC) at CERN announced the discovery of the Higgs boson, Perimeter hosted this invitation-only workshop for over 40 leading theorists and experimentalists from the Compact Muon Solenoid (CMS) experiment at the LHC to discuss the results and plan future experiments. The conference was both timely and effective in fostering the cross-pollination of ideas between the worlds of theory and experiment.

- **"Emergence and Entanglement II"** (May 6-10, 2013): Building on the success of the first workshop held at Perimeter in 2010, this conference brought together 40 top scientists in the rapidly-evolving field of quantum matter, including eight Distinguished Visiting Research Chairs. In line with Perimeter's philosophy, the conference provided unique perspectives on cutting-edge developments and was highly multidisciplinary, involving researchers from condensed matter and quantum information to computational physics and string theory.

- **"Cosmological Frontiers in Fundamental Physics 2013"** (July 8-11, 2013): Supported by the Templeton Frontiers Program at Perimeter Institute, the seventh workshop in a long-running series brought together 80 researchers to discuss the new data just released from the Planck satellite, which is revealing the universe in unprecedented detail.

- **"Loops 13"** (July 22-26, 2013): Perimeter's final conference of 2012/13 welcomed nearly 200 researchers, ranging in age from 17 to 75, for 21 plenary talks and 133 parallel sessions – all aimed at reconciling the theories of quantum mechanics and general relativity. "Loops 13" was also supported by the Templeton Frontiers Program at Perimeter Institute.

Seminars and Colloquia

Seminars and colloquia foster collaboration and share knowledge from leading researchers around the globe, invigorating the Institute's research community. In 2012/13, Perimeter exceeded its targeted outcomes, holding 257 seminars and 44 colloquia. Particularly notable were talks by DVRCs Ganapathy Baskaran, Ted Jacobson, Renate Loll, Subir Sachdev, Paul Steinhardt, Steven White, and Mark Wise.

Quantum Information and Student Conference," University of Calgary; (9) "Women in Physics Canada," Simon Fraser University; and (10) "TRIUMF," TRIUMF.

Courses

When possible, Perimeter seeks to capitalize on the expertise of its resident and visiting scientists by having them give topical courses on cutting-edge areas. These courses are open to students of surrounding universities, thereby enhancing course offerings.

In 2012/13, Perimeter offered two advanced for-credit courses: “Elements of General Relativity,” taught by Senior Researcher Rafael Sorkin, and “Supersymmetry,” taught by Associate Faculty member Alex Buchel. In addition, while visiting as part of Perimeter’s partnership agreement with the Institute of Mathematical Sciences, Chennai, postdoctoral fellow Steve Avery gave a mini-course entitled, “Fuzzballs to Firewalls: A Post-Firewall Review of the Fuzzball Proposal.” Lastly, Perimeter opened up 10 PSI courses to students at surrounding universities as three-week, non-credit mini-courses.

Perimeter Institute Recorded Seminar Archive (PIRSA)

- 81,099 unique visitors from 170 countries accessed PIRSA, up 7.5 percent over last year
- New and returning users accessed PIRSA more frequently, with 737,515 page views, up 9.5 percent from 2011/12

Nearly all talks held at Perimeter can be viewed online on the Perimeter Institute Recorded Seminar Archive (PIRSA) at www.pirsa.org. This permanent, free, searchable, and citable archive of video-recorded seminars, conferences, workshops, and courses was developed by the Institute to share knowledge with the international scientific community. It is an important resource for the field, as evidenced by the continued rise in site traffic every year.

Objective 8: To engage in high impact outreach

Summary of Achievements

- Reached over one million students through Perimeter programs and in-class resources, bringing the total to more than 2.5 million students to date
- Director Neil Turok delivered the 2012 Massey Lectures to sold-out audiences across Canada, and the associated book became a Canadian bestseller
- Held the "Inspiring Future Women in Science" conference for 160 Ontario high school students
- Hosted the 11th annual International Summer School for Young Physicists (ISSYP), held five one-day GoPhysics! camps, and gave 10 Physica Phantastica presentations – reaching a total of more than 2,400 students across Canada
- Delivered 90 workshops to more than 2,500 educators throughout Canada and abroad, impacting over 185,000 students
- Launched *Career Moves: Skills for the Journey*, a new in-class resource for high school students
- Updated existing resources to facilitate international sale and distribution
- Presented 10 sold-out talks on compelling scientific topics as part of the Perimeter Public Lecture Series

Highlights

Student Programs and Products

International Summer School for Young Physicists (ISSYP)

- Hosted the 11th successful year of ISSYP for 40 top Canadian and international students[27]

The International Summer School for Young Physicists (ISSYP) is a pillar of Perimeter's outreach efforts. The program brings Canadian and international students with demonstrated scientific potential to Perimeter for a two-week immersion in modern physics, including mentoring sessions with resident researchers and lab tours of the Institute's experimental partners. By providing a first-hand experience of cutting-edge research at an age when students are actively weighing career directions, Perimeter is developing new talent for the field and for Canada.[28] Follow-up metrics indicate that over 70 percent of ISSYP alumni credit the program with inspiring them to pursue a career in math or physics.

[27] This included 20 Canadians from eight provinces and territories and 20 international students from 11 countries. An emphasis is placed on ensuring an even gender split – 20 boys and 20 girls.

[28] Follow-up surveys indicate that ISSYP alumni have gone on to study at a host of top international institutions, as well as a long list of Canadian universities.

In 2012/13, for the first time, ISSYP students received an in-depth, take-away resource on quantum mechanics, made possible by the generous support of the RBC Foundation (see Objective 10).

"Inspiring Future Women in Science" Conference

- Held a one-day conference for 160 young women from high schools around southern Ontario

Science has historically been a male-dominated field, but Perimeter Institute is trying to change that. On March 7, 2013, Perimeter hosted "Inspiring Future Women in Science," a conference which brought 160 young women from 32 southern Ontario high schools to the Institute to learn more about the rewards, challenges, and possibilities of a career in science, technology, engineering, or mathematics (STEM). The conference included a keynote address from NASA scientist Dr. Adriana Ocampo, a panel discussion with women scientists, and mentoring sessions. The conference was very well received by participants and may become a biennial event.

GoPhysics!

- Held five GoPhysics! camps across Canada, reaching more than 135 students

GoPhysics! is a one-day program that gives a snapshot of the ISSYP experience to approximately 25 students at a time. Given by Perimeter Teacher Network associates and outreach staff scientists, it is designed to get high-potential senior high school students excited about modern physics. In 2012/13, the camps were held strategically in the cities Director Neil Turok was visiting on his Massey Lecture tour – St. John's, Montreal, Toronto, Calgary, and Vancouver.

Physica Phantastica

- Delivered 10 presentations to over 2,200 students in grades 7 to 12, plus two presentations for the general public that reached over 200 people

Physica Phantastica presentations provide entertaining and accessible introductions to modern physics, illustrating the connections between foundational science and the technologies that enhance our lives.

Aboriginal Engagement

- Reached over 1,500 Aboriginal youth in more than 60 rural and remote communities through partnerships with Actua and the Indigenous Education Coalition

In order to effectively engage Aboriginal youth, outreach staff train associates from partner organizations on Perimeter resources; they, in turn, deliver the content to Aboriginal students throughout the country as part of their established outreach systems. Perimeter has been working with

Actua, Canada's leading science, technology, engineering, and mathematics (STEM) outreach organization for youth, particularly among Aboriginal Canadians, for a year and a half. In 2012/13, Perimeter staff also trained associates from the Indigenous Education Coalition to share the resources, increasing the number of youth reached.

Programs and Resources for Teachers

Teacher Network

- Teacher Network members delivered 50 workshops to nearly 900 educators, thereby reaching more than 65,000 Canadian high school students

Consisting of over 60 teachers from across Ontario and Canada, members of Perimeter's Teacher Network are trained on sharing Perimeter's resources with fellow educators. Most are alumni of Perimeter's EinsteinPlus Teachers' Workshop, an annual one-week summer workshop for high school educators which shares effective strategies for teaching modern physics. Network members conducted 50 workshops in their home districts this year, thereby greatly extending the reach of the Institute's resources to some 65,000 Canadian high school students.[29]

On-location Teacher Workshops and Conference Presentations

- Outreach staff delivered 40 on-location workshops at teacher conferences in Canada and abroad, reaching over 1,600 educators and exceeding targeted outcomes

Presentations at major educational conferences and gatherings are a cost-effective means of increasing the visibility of outreach products and programs, both within Canada and abroad. In particular, Perimeter's outreach team has tried to engage grade 9 and 10 teachers, given the expansion of the Institute's resources in recent years to include younger students.

In 2012/13, Perimeter staff presented at the annual conferences of the Science Teachers' Association of Ontario (STAO), the Ontario Association of Physics Teachers (OAPT), the Physics Teaching Resource Agents (PTRA), the National Science Teachers Association (NSTA), and the American Association of Physics Teachers (AAPT), among others. They also reached 50 teachers at the High School Teachers (HST) Program at CERN in Switzerland and 200 teachers at the National Physics Education Seminar in Singapore.

[29] A planned weekend training conference for up to 30 Teacher Network educators in July 2013 was postponed to August 2013 to meet the needs of participant teachers.

Educational Resources

Perimeter Inspirations, Explorations, and *Investigations*

- Completed a new *Perimeter Explorations* module, *Career Moves: Skills for the Journey*, in both French and English
- Perimeter's in-class educational modules have cumulatively reached over two million students to date

Produced with the input of physics educators and scientists, in-class modules are the Institute's primary means of introducing Canadian high school students to modern physics. Feedback indicates that they are used and re-used in classrooms, multiplying their impact over time.

The Institute employs a balanced approach to educational product creation. ***Inspirations*** content aims to intrigue high school students and motivate them to continue with math and science in senior grades. ***Explorations*** modules deliver more challenging ideas and technical content to senior high school students, preparing them for post-secondary education in math, science, and engineering. ***Investigations*** modules are simple, classroom-ready demonstrations or lab activities.

Career Moves: Skills for the Journey, the newest *Explorations* module, was launched in 2012/13. Created with support from the Federal Economic Development Agency for Southern Ontario (FedDev Ontario), it is designed to inspire students with the career possibilities of STEM subjects (science, technology, engineering, and math) by connecting them with creativity, critical thinking, imagination, and the entrepreneurial spirit. It was designed with extensive input from teachers and experienced guidance counsellors.

International Distribution

- Launched strategy to sell educational resources internationally

Perimeter resources will continue to be offered free to Canadian educators, but, as part of a cost-recovery strategy, they are available for sale outside of Canada.

First steps toward full implementation of this strategy were undertaken in 2012/13. Several existing resources (e.g., *The Physics of Innovation* and *Measuring Planck's Constant*) were updated and adapted for international audiences, and an online store was created. The first major sale – a large suite of educational modules, plus training on the resources – was made to the Ministry of Education in Singapore (which consistently ranks among world leaders in STEM education). Perimeter staff delivered the training in Singapore in June 2013.

Online Resources

Publishing high-quality resources online allows Perimeter to scale its reach and impact. With the launch of its updated website in fall 2012, a huge trove of Outreach content was put online, including *Perimeter Inspirations*, *Explorations*, and *Investigations* content, *Virtual ISSYP*, over 30 *Meet A Scientist* video interviews, and an archive of past Public Lectures. As noted above, the new website also contains an order management module to support sales and shipping of Perimeter's resources (see Objective 9).

In addition, staff leveraged the exposure brought about by the Massey Lectures (see below) to expand the Institute's social media network, primarily through Facebook, Twitter, and YouTube. Perimeter's Twitter following, for example, grew over 60 percent, to more than 5,500 followers.[30]

Finally, Perimeter began production on four short educational 'interstitial' programs for viewing online and via media partners, but completion dates were moved back due to hurdles experienced by the Institute's production partner, TVO.

Programs for the General Public

2012 Massey Lectures

The Massey Lectures are an annual highlight of Canada's intellectual life, in which distinguished thinkers share original insights on subjects of contemporary interest. A joint venture of CBC, the House of Anansi Press, and Massey College, the lectures are delivered live across Canada, broadcast on radio, and published as a book.

In October 2012, Perimeter Director Neil Turok delivered the 2012 Massey Lectures to sold-out audiences across Canada. The lectures surveyed how humanity has uncovered the universe's workings in the past and gave a visionary look at how science can shape the future. The lectures helped to increase scientific literacy and appreciation among the general public; the associated book, *The Universe Within: From Quantum to Cosmos,* ensures they will continue to do so for years to come.

Highlights of the Massey Lectures include:

- The lectures reached over one million people across Canada.
- Perimeter's outreach team visited each host city – St. John's, Montreal, Toronto, Calgary, and Vancouver – prior to Turok's lectures, giving presentations in local schools to engage students on science connected to the lectures.
- Staff assisted the Massey team with communications, resulting in increases over recent years in on-site attendance, radio listenership, book sales, online engagement, and media coverage.

[30] During the Massey Lectures, Perimeter reached 1.9 million Twitter followers through interactions with influencers including CERN, Cory Doctorow, and Margaret Atwood. Perimeter's Facebook posts received 17,384 impressions, more than 1,000 click-throughs, over 500 'likes,' and 335 shares.

- *The Universe Within: From Quantum to Cosmos* became a Canadian bestseller, and Neil Turok was awarded the 2013 Lane Anderson Award, which honours excellence in Canadian science writing.

Public Lecture Series

Perimeter's flagship Public Lecture Series, presented by Sun Life Financial, continued to be extremely popular (although admission is free, tickets are required, and all 600 are generally claimed within hours of becoming available). The lectures are professionally recorded and made available online through Perimeter's website and iTunes University; select talks are also broadcast on TVO.

In 2012/13, Perimeter presented 10 accessible, engaging talks on scientific topics – including two off-site lectures in Toronto and Ottawa – meeting targeted objectives. Two of this year's lectures (by Neil Turok and Lee Smolin) were held at the Institute and simulcast online. Other highlights included Dr. Paul Steinhardt on his epic search for the world's first naturally occurring quasi-crystal and popular science writer Jennifer Ouellette on the many practical applications of calculus.

Waterloo Global Science Initiative (WGSI)

The Waterloo Global Science Initiative (WGSI) is an independently funded, non-profit partnership between Perimeter Institute and the University of Waterloo. Every two years, WGSI fosters international, multigenerational, and interdisciplinary collaborations on key topics to advance novel ideas for a more secure, sustainable, and prosperous future.

In 2012/13, the WGSI team continued impact activities tied to its inaugural conference, Equinox Summit: Energy 2030 (held in 2011), and initiated planning for the second WGSI event (to be held in the fall of 2013), meeting targeted objectives.

The BrainSTEM: Your Future is Now Festival

In line with Perimeter's objective of hosting a major festival or public event every other year, planning commenced in November 2012 to host the BrainSTEM: Your Future is Now Festival in the fall of 2013.

The festival's primary objective is to engage and excite young people about science and the many entrepreneurial opportunities it holds for their futures. Accordingly, highly interactive exhibits and engaging public lecture speakers are planned. The BrainSTEM: Your Future is Now Festival is supported by the Federal Economic Development Agency for Southern Ontario (FedDev Ontario).

Media Engagement and Professional Development

As part of its efforts to communicate science accurately to lay audiences, Perimeter's communications staff fulfills information requests from quality media outlets and provides assistance to researchers on communicating science to the general public.[31]

Throughout 2012/13, staff provided information and commentary to journalists and writers at numerous national and international print and online outlets. Highlights can be accessed in Appendix G: Media Highlights, some of which are noted below:

- Neil Turok's 2012 Massey Lectures were covered extensively in national and international print, broadcast, and online outlets.[32]
- Perimeter researchers were noted in a variety of science stories in the *National Post*, *Popular Mechanics*, *Science Daily*, Phys.org, *MIT Technology Review*, and *New Scientist*, among others.

[31] For example, noted science writer and editor David Harris (founding editor of *Symmetry* magazine) gave a workshop on science communication to Perimeter staff and researchers in June 2013.

[32] These included *TIME*, *Reader's Digest*, *The Globe and Mail*, *National Post*, and *Maclean's*, plus major daily newspapers across Canada, including *The Telegram* (St. John's), *Toronto Star*, *Calgary Herald*, and *Vancouver Sun*. Online outlets that covered the Masseys included the CBS News Blog, *Boing Boing*, io9, *The Georgia Straight*, and *The Tyee*.

Objective 9: To create the world's best environment and infrastructure for theoretical physics research, training, and outreach

Summary of Achievements

- Launched a new website to better serve core audiences, including modules to process individual donations and international sales of educational outreach resources
- Implemented a new content management platform to streamline reporting, communications, and process management
- Upgraded meeting room technologies to support long-distance collaboration
- Expanded library collections, including electronic access to key journals
- Commissioned a study on the climate for women at Perimeter in an effort to promote gender equity

Highlights

IT Systems Upgrades and Initiatives

In fall 2012, Perimeter launched a redesigned website to better serve core audiences, providing enhanced functionality and usability. The new site can also process individual donations as Perimeter grows its base of private supporters (see Objective 10) and support the sales and shipping of the Institute's educational outreach resources (see Objective 8).

A new building-wide digital signage system was launched in early 2013. This system (and an intranet portal slated for launch in 2014) draws content from the website's content management platform, allowing the Institute to realize efficiencies, streamline reporting, and reduce redundant inputting of information.

Planned upgrades to IT infrastructure to optimize research and realize administrative efficiencies continued in line with targeted objectives. These included:

- Completed RECAST, a globally accessible IT framework for the re-use of existing high energy physics analyses for new models
- Migrated most server and storage infrastructure to a commercial collocation facility, ensuring increased data stability while reducing costs
- Upgraded meeting rooms to support long-distance research collaboration via web conferencing, self-recording, and screen-sharing

E-Journal Access and Library Collections

In 2012/13, Perimeter continued to expand its collections, in line with a multi-year strategy to provide resident and visiting researchers with comprehensive research resources. The library added 204 new texts, bringing the total to 5,203 in the print collection (5,621 in all formats), and added electronic subscriptions to 115 journals that researchers and students can access on-site and remotely.

Promoting Gender Equity

Perimeter is committed to showing leadership in combatting the traditional gender imbalance in physics. Thus, at the Institute's request, a four-woman team of senior scientists from the American Physical Society's (APS) Committee on the Status of Women in Physics (CSWP) conducted a two-day site visit in May 2013 to examine the climate for women at the Institute.

The committee's report endorsed Perimeter's commitment to this initiative, while offering several recommendations on how to achieve greater gender equity throughout the Institute.[33] These recommendations are now being reviewed by senior Perimeter staff.

[33] These include, among other things, fostering more regular and informal feedback and peer advice for PhD students and junior research staff; determining whether unconscious biases are directing female researchers disproportionately to PSI Fellow teaching roles among postdoctoral fellows; and continued training in diverse hiring practices, such as the STRIDE workshops from the University of Michigan.

Objective 10: To continue to build on Perimeter's highly successful public/private partnership funding model

Summary of Achievements

- ✓ Attracted over $1.6 million from individuals, corporations, and foundations
- ✓ Launched the Corporate Partners Program, Emmy Noether Circle, and Friends and Alumni Program
- ✓ Hired Jonathan Braniff as Chief Advancement Officer
- ✓ Secured $100,000 to create the Anaximandros Scholarship for young physicists

Highlights

Public Partners

Perimeter Institute is funded through an innovative public/private partnership, which shares the opportunities and benefits of long-term investment in fundamental research. Investment from all levels of government helped establish Perimeter and sustained support from the public sector has been critical to the Institute's success to date.

2012/13 marked the first year of a $50 million funding agreement with the Government of Canada and the second year of a $50 million funding agreement with the Province of Ontario. In line with targeted objectives, Perimeter continues to utilize best practices in financial management and meet all its reporting requirements.

Private Partners

- ➢ Obtained new private sector donations of over $1 million from individuals and corporations over the last year, an increase of $300,000 over 2011/12

To support the private side of its funding model, Perimeter actively pursues support from individuals, corporations, and foundations. To drive private sector donations, Perimeter has created several funding circles, including:

- ➢ **The Corporate Partners Program**, which seeks to connect Perimeter with private companies giving up to $100,000 per year; contributions totalling $200,000 were received from existing corporate sponsors including the RBC Foundation, Sun Life Financial, and Canadian Tire Corporation Ltd., with several new donors expected in 2013/14

- **The Director's Circle** for individuals giving $10,000 or more, which continued to grow and now has a total of 48 members
- **The Emmy Noether Circle**, which specifically supports women in science and has attracted pledges of $105,000 over three years from the Bluma Appel Community Trust and $250,000 over five years from the Ira Gluskin and Maxine Granovsky Gluskin Charitable Foundation
- **The Friends and Alumni Program**, a new program to cultivate individual donors giving up to $1,000, which grew to 197 members

In addition to the programs above, $100,000 in equal commitments ($50,000 each) was received from the Hellenic Heritage Foundation and the Savvas Chamberlain Family Foundation to create the Anaximandros Scholarship, named for the ancient Greek philosopher believed to have conducted the earliest recorded scientific experiment. Beginning in the fall of 2014, the scholarship will allocate $10,000 per year to support the education and training of an exceptional graduate student at Perimeter.

Building on the success of Neil Turok's 2012 Massey Lecture tour (see Objective 8), the Institute built its profile substantially across the country in the corporate, government, and philanthropic communities, with targeted events in Vancouver, Calgary, Toronto, Montreal, and Ottawa.

On the international front, similar events were held in New York City and Los Angeles (hosted by Canada's Consul General). Targeted follow-up activities are ongoing with prospective supporters.

Chief Advancement Officer

In April 2013, Perimeter welcomed Jonathan Braniff as its Chief Advancement Officer, concluding an intensive, one-year international search. Braniff has over 15 years of fundraising experience, working throughout Canada, the United States, Ireland, and the United Kingdom on capital and endowment campaigns, feasibility and planning studies, strategic consulting, and development audits. Cumulatively, he has helped organizations raise over $300 million from individuals, corporations, foundations, trusts, and governments. Since arriving at Perimeter, Braniff has begun to develop a three-year advancement plan to expand and broaden the Institute's private donor base.

Executive Committee of the Perimeter Leadership Council

Perimeter's Leadership Council is a group of prominent individuals who volunteer their time, offer guidance, and act as ambassadors for Perimeter to the business and philanthropic communities. In 2012/13, Perimeter established an Executive Committee to help coordinate and oversee the activities of the Leadership Council as it grows. In addition to Council Co-Chairs Mike Lazaridis, Cosimo Fiorenza, and Jon Dellandrea, the Executive Committee consists of Catherine (Kiki) Delaney, Arlene Dickinson, Carol Lee, and Maureen Sabia.

Overview of Financial Statements, Expenditures, Criteria, and Investment Strategy

Summarized Financial Statements of

PERIMETER INSTITUTE

Year Ended July 31, 2013

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REPORT OF THE INDEPENDENT AUDITORS ON THE SUMMARY FINANCIAL STATEMENTS

To the Directors of
Perimeter Institute

The accompanying summary financial statements, which comprise the summary statement of financial position as at July 31, 2013 and the summary statement of operations and changes in fund balances for the year then ended, are derived from the audited financial statements of Perimeter Institute (the "Institute") for the year ended July 31, 2013. We expressed an unmodified audit opinion on those financial statements in our report dated December 6, 2013. Those financial statements, and the summary financial statements, do not reflect the effects of events that occurred subsequent to the date of our report on those financial statements.

The summary financial statements do not contain all the disclosures required by Canadian accounting standards for not-for-profit organizations. Reading the summary financial statements, therefore, is not a substitute for reading the audited financial statements of the Institute.

Management's Responsibility for the Summary Financial Statements

Management is responsible for the preparation of a summary of the financial statements in accordance with Canadian accounting standards for not-for-profit organizations.

Auditor's Responsibility

Our responsibility is to express an opinion on the summary financial statements based on our procedures, which were conducted in accordance with Canadian Auditing Standard (CAS) 810, "Engagements to Report of Summary Financial Statements."

Opinion

In our opinion, the summary financial statements derived from the audited financial statements of the Institute for the year ended July 31, 2013 are a fair summary of those financial statements, in accordance with Canadian accounting standards for not-for-profit organizations.

Zeifmans LLP

Toronto, Ontario
December 6, 2013

Chartered Accountants
Licensed Public Accountants

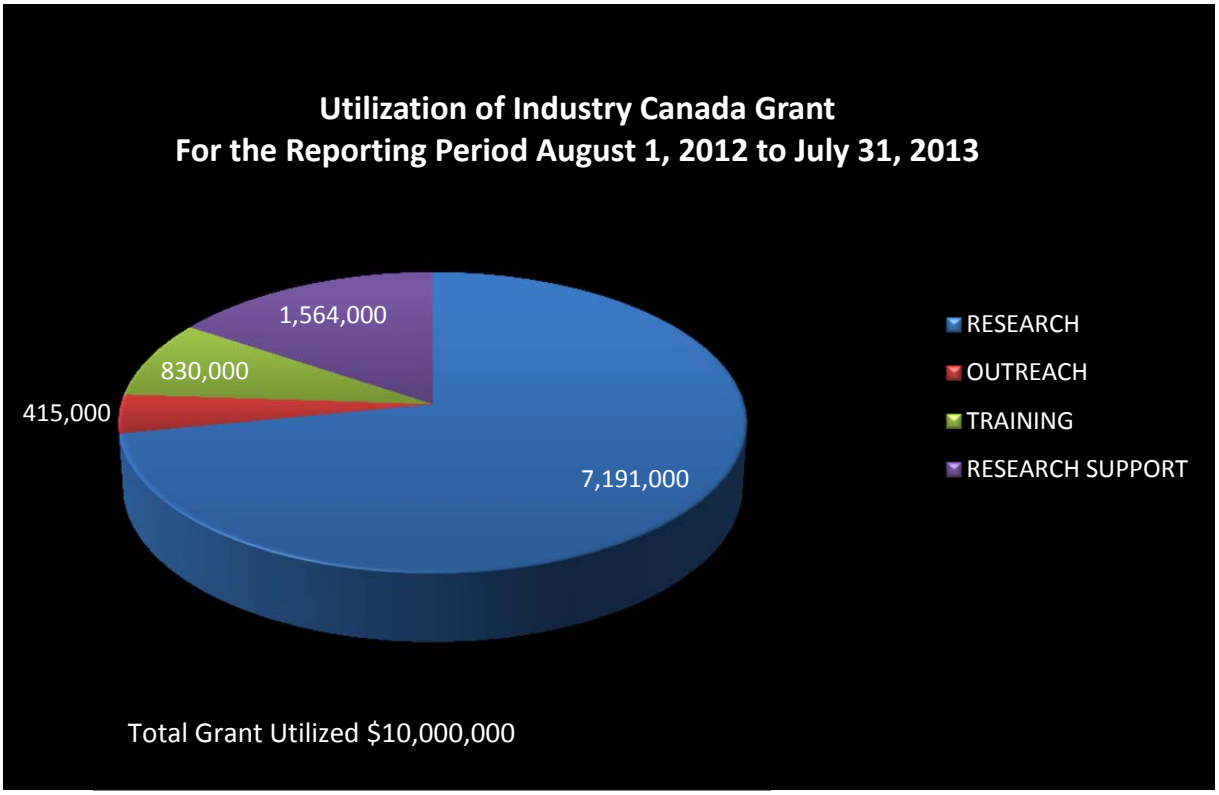
PERIMETER INSTITUTE
Summarized Statement of Financial Position
as at July 31, 2013

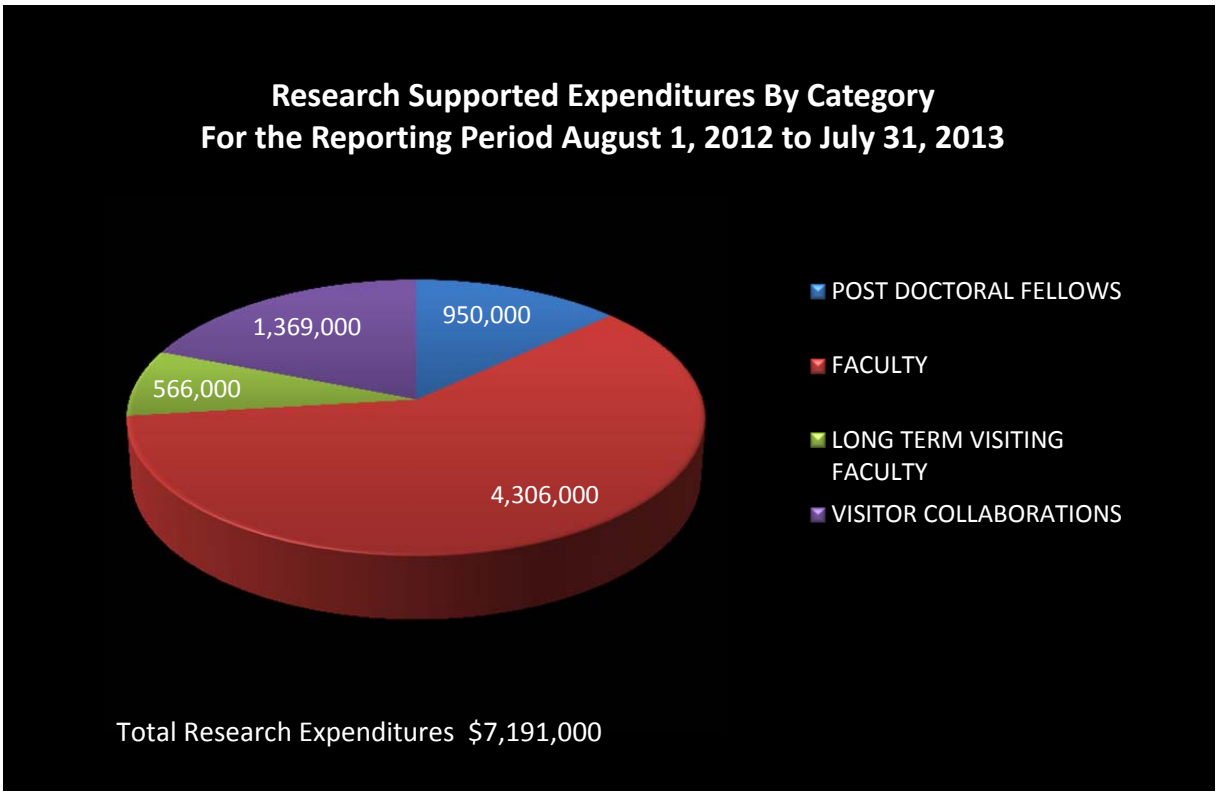
	2013	2012
ASSETS		
Current Assets:		
Cash and cash equivalents	$ 11,774	$ 1,697
Marketable securities	232,514	211,417
Government grants receivable	2,321	4,294
Assets held for sale	---	1,235
Other current assets	1,599	1,151
	248,208	219,794
Property and equipment	52,808	55,281
TOTAL ASSETS	$ 301,016	$ 275,075
LIABILITIES AND FUND BALANCE		
Current liabilities:		
Bank overdraft	$ ---	$ 732
Bank indebtedness	---	2,245
Accounts payable and other current liabilities	2,487	2,331
TOTAL LIABILITIES	2,487	5,308
Fund balances:		
Invested in capital assets	52,319	56,495
Externally restricted	126,801	105,589
Internally restricted	78,840	78,840
Unrestricted	40,569	28,843
TOTAL FUND BALANCES	298,529	269,767
	$ 301,016	$ 275,075

PERIMETER INSTITUTE
Summarized Statement of Operations and Changes in Fund Balances
For the Year Ended July 31, 2013

	2013	2012
Revenue		
Government grants	$ 23,837	$ 14,412
Other income	1,446	741
Donations	909	1,142
	26,192	16,295
Expenditures		
Research	11,913	11,025
Research training	1,983	1,838
Outreach and science communications	3,080	3,350
Indirect research and operations	5,697	5,649
	22,673	21,862
Excess of revenue over expenses (expenses over revenue) before investment income, amortization and gain on disposal of property and equipment	3,519	(5,567)
Amortization	(4,129)	(4,098)
Gain on disposal of property and equipment	771	8
Investment income	28,601	7,645
Excess of revenue over expenses (expenses over revenue)	28,762	(2,012)
Fund balances, beginning of year	269,767	271,779
Fund balances, end of year	$ 298,529	$ 269,767

Expenditure of Industry Canada Grant





Performance Evaluation Strategy

Scientific

Perimeter Institute has a wide array of performance monitoring and evaluation policies, systems, and processes (both internal and external) that have been developed over the years and are re-evaluated and updated on a regular basis. These initiatives to measure outcomes, results, and impact include:

Performance Monitoring – Internal

- Annual reports on research activity submitted to the director by all faculty and associate faculty members for evaluation
- Annual performance reviews of all research staff
- Ongoing monitoring of publication and citation records
- Post-conference reports and evaluation
- Visitor research activity reports and ongoing tracking of all output
- Regular updates and monitoring of progress of all scientific programs
- Mid-term researcher performance reviews
- Postdoctoral fellow mentorship program
- Monitoring of postdoctoral fellows' post-Perimeter placement success
- Monitoring of researchers' international presence and impact through collaborations and invitations to lecture
- Internal review and evaluation process of all outreach programs and products

Performance Monitoring – External

- Regular reporting to international Scientific Advisory Committee (SAC) with subsequent performance assessment and recommendations (see Appendix F for a list of SAC members)
- Review of faculty hires and promotions by Scientific Advisory Committee
- Peer review of publications
- Performance audits and reviews as per granting agreements
- External review and evaluation process of all outreach programs and products
- Performance audits in accordance with grant agreements

Investment Strategy

Public/Private Partnership

Perimeter Institute exists through a cooperative and highly successful public/private approach to investment that provides for ongoing operations while, at the same time, safeguarding future opportunities.

Public partners contribute to research, training, and outreach activities and, in keeping with individual grant requirements, receive ongoing updates, reports, and yearly audited financial statements as required to ensure value for money while remaining aware of the Institute's research productivity and outreach impact.

Private funds from a continuously growing donor base are used, in part, to fund operations, while a portion is protected in an endowment that is primarily designed to receive and increase donated monies by maximizing growth and minimizing risk in order to contribute to the strongest possible long-term financial health of the Institute.

Perimeter Institute continues to be an innovative example of a public/private partnership, uniting government and philanthropists in a common quest to secure the transformative potential of scientific research in Canada.

Governance

Perimeter Institute is an independent not-for-profit corporation governed by a volunteer Board of Directors drawn from the private sector and academic community. The Board is the final authority on all matters related to the general structure and development of the Institute (see Appendix E: Board of Directors).

The Board of Directors is supported in fulfilling its fiduciary responsibilities with respect to financial management of the Institute through two Board committees. The Investment Committee is responsible for overseeing the investment and management of funds received according to a Board-approved investment policy that outlines guidelines, standards, and procedures for the prudent investment and management of funds. The Finance and Audit Committee is responsible for overseeing Perimeter Institute's policies, processes, and activities in the areas of accounting, internal controls, risk management, auditing, and financial reporting. The Board also forms other committees as required to assist it in discharging its duties.

Reporting to the Board of Directors, the Institute's Director is a pre-eminent scientist responsible for developing and implementing the overall strategic direction of the Institute. The Chief Operating Officer (COO) reports to the Director and is in charge of day-to-day operations. Support to the COO is provided by a team of senior administrative staff. The Institute's resident scientists play an active role in scientific

operational issues via participation on various committees in charge of scientific programs and report to the Director.

The Scientific Advisory Committee (SAC), comprised of eminent international scientists (see Appendix F: Scientific Advisory Committee), offers independent scrutiny and advice, helping to ensure Perimeter's activities meet high standards of scientific excellence. Members serve three-year terms and participate in regular meetings held at the Institute to thoroughly review PI's scientific, training, and educational outreach programs, after which the Chair writes a report to the Board of Directors and the Institute Director.

Objectives for 2013/14

The successes outlined in the preceding pages provide strong evidence that the Institute's strategic planning has been both sound and effective, and that it is on track to achieve its long-term goal: to create and sustain a world-leading centre for foundational theoretical physics research, training, and outreach that will promote scientific excellence and stimulate breakthroughs.

In the coming year, the Institute will continue upon its present course in order to advance its core mission and goals, based upon the following strategic objectives.

Statement of Objectives, 2013/14

Objective 1: To deliver world-class research discoveries

Objective 2: To become the research home of a critical mass of the world's leading theoretical physicists

Objective 3: To generate a flow-through of the most promising talent

Objective 4: To become the second research home for many of the world's outstanding theorists

Objective 5: To act as a hub for a network of theoretical physics and math centres around the world

Objective 6: To increase Perimeter's role as Canada's focal point for foundational physics research

Objective 7: To host timely, focused conferences, workshops, seminars, and courses

Objective 8: To engage in high impact outreach

Objective 9: To create the world's best environment and infrastructure for theoretical physics research, training, and outreach

Objective 10: To continue to build on Perimeter's highly successful public/private partnership funding model

Appendices

Note: Where applicable, appendices reflect the Perimeter community as of July 31, 2013.

Appendix A: Top 100 Physics and Astronomy Institutions Worldwide, Drawn from Excellence Map Analysis

Perimeter was ranked fifth overall in physics and astronomy, and second in theoretical physics, behind only the renowned Institute for Advanced Study in Princeton, and above such traditional centres of excellence as Harvard University, Stanford University, and the Massachusetts Institute of Technology. The next Canadian institution to appear on this list was the University of Victoria, ranked 78th.

No.	Institution	Country	Papers	Probability of excellent papers
1	Institut de Ciencies Fotoniques	ESP	522	0.328
2	Institute for Advanced Study	USA	558	0.309
3	Institucio Catalana de Recerca i Estudis Avancats	ESP	771	0.297
4	Rice University	USA	1294	0.294
5	Perimeter Institute for Theoretical Physics	CAN	708	0.293
6	University of Pennsylvania	USA	1699	0.279
7	Stanford University	USA	3560	0.276
8	Partners HealthCare System	USA	635	0.276
9	Harvard University	USA	5254	0.274
10	University of California, Santa Barbara	USA	3772	0.274
11	Columbia University	USA	2399	0.269
12	Massachusetts Institute of Technology	USA	5880	0.269
13	Princeton University	USA	3595	0.266
14	Tufts University	USA	529	0.263
15	University of Chicago	USA	2192	0.261
16	University of California, Santa Cruz	USA	2525	0.260
17	Carnegie Institution for Science	USA	785	0.257
18	Institut de Fisica d'Altes Energies	ESP	621	0.255
19	Boston University	USA	1594	0.254
20	Ludwig-Maximilians Universitat Munchen	DEU	1981	0.253
21	New York University	USA	921	0.253
22	University of California, Berkeley	USA	5006	0.252
23	Yale University	USA	2082	0.251
24	Universitat Innsbruck	AUT	749	0.250

25	Duke University	USA	1622	0.250
26	Wayne State University	USA	861	0.248
27	University of Washington	USA	2525	0.247
28	Fermi National Accelerator Laboratory	USA	1620	0.247
29	Ohio State University, Columbus	USA	2661	0.243
30	Helsinki Institute of Physics	FIN	774	0.242
31	Cornell University	USA	2879	0.241
32	University of Illinois, Chicago	USA	1591	0.241
33	University of California, Los Angeles	USA	3484	0.240
34	Universite Blaise Pascal, Clermont-Ferrand II	FRA	746	0.238
35	California Institute of Technology	USA	5234	0.238
36	University of Massachusetts, Amherst	USA	1389	0.236
37	General Atomics	USA	640	0.236
38	Rensselaer Polytechnic Institute	USA	1218	0.235
39	Virginia Polytechnic Institute and State University	USA	1005	0.235
40	University of Rochester	USA	2023	0.235
41	Universite de Geneve	CHE	1500	0.234
42	Friedrich-Schiller-Universitat Jena	DEU	1171	0.233
43	National Institute for Subatatomic Physics	NLD	994	0.233
44	Northwestern University, Evanston	USA	2473	0.233
45	Universite d'Evry-Val d'Essonne	FRA	560	0.232
46	George Mason University	USA	516	0.232
47	Institute for High Energy Physics	RUS	1011	0.231
48	Osterreichische Akademie der Wissenschaften	AUT	1106	0.230
49	Syracuse University	USA	578	0.230
50	Lawrence Berkeley National Laboratory	USA	4850	0.230
51	Stanford Linear Accelerator Center	USA	1603	0.230
52	Alcatel-Lucent	USA	581	0.230
53	École Polytechnique Federale de Lausanne	CHE	2905	0.229
54	Universitat Basel	CHE	769	0.229
55	University of Twente	NLD	1069	0.229
56	University of California, Riverside	USA	1372	0.229
57	Scuola Normale Superiore Pisa	ITA	1102	0.228
58	National Renewable Energy Laboratory	USA	728	0.228
59	Radboud University Nijmegen	NLD	970	0.227
60	University of California, Davis	USA	2173	0.227
61	University of California, Irvine	USA	2039	0.227
62	Carnegie Mellon University	USA	1424	0.226
63	Indiana University-Bloomington	USA	1199	0.226
64	University of Hawaii, Manoa	USA	1300	0.225

65	Swiss Federal Institute of Technology (ETH)	CHE	3431	0.224
66	University of Mississippi	USA	720	0.224
67	Australian Research Council	AUS	955	0.223
68	Northeastern University	USA	773	0.222
69	Purdue University	USA	2243	0.222
70	Smithsonian Institution	USA	2225	0.222
71	University of Michigan, Ann Arbor	USA	3791	0.222
72	University of New Mexico	USA	1175	0.221
73	IBM Corporation	USA	1003	0.221
74	Johns Hopkins University	USA	2424	0.220
75	Rutgers, The State University of New Jersey	USA	1890	0.220
76	University of Pittsburgh	USA	1365	0.219
77	The University of Queensland	AUS	1011	0.218
78	University of Victoria	CAN	854	0.218
79	University of Kansas	USA	689	0.218
80	College de France	FRA	766	0.217
81	Oklahoma State University, Stillwater	USA	581	0.217
82	Brown University	USA	1051	0.216
83	Universitat Konstanz	DEU	507	0.215
84	Max Born Institut fur Nichtlineare Optik und Kurzzeitspektroskopie	DEU	536	0.215
85	Weizmann Institute of Science	ISR	1717	0.215
86	Kansas State University	USA	755	0.215
87	University of Texas, Austin	USA	2976	0.215
88	University of California, San Diego	USA	3340	0.215
89	Leiden University	NLD	1318	0.213
90	Albert-Ludwigs-Universitat Freiburg im Breisgau	DEU	1056	0.212
91	Universita degli Studi di Trieste	ITA	1347	0.212
92	Pennsylvania State University	USA	3287	0.212
93	University College Dublin	IRL	661	0.211
94	University of Colorado, Boulder	USA	2421	0.211
95	University of Glasgow	GBR	1464	0.210
96	Panjab University	IND	733	0.210
97	University of Cincinnati	USA	969	0.210
98	Space Telescope Science Institute	USA	806	0.210
99	University of Maryland, College Park	USA	4037	0.210
100	The University of Edinburgh	GBR	1771	0.208

Appendix B: Faculty and Associate Faculty Members

Faculty

Neil Turok (PhD Imperial College London, 1983) was Professor of Physics at Princeton University and Chair of Mathematical Physics at the University of Cambridge before assuming his current position as Director of Perimeter Institute. Turok's research focuses on developing fundamental theories of cosmology and new observational tests. His predictions for the correlations of the polarization and temperature of the cosmic background radiation (CBR) and of the galaxy-CBR correlations induced by dark energy were recently confirmed. With Stephen Hawking, he discovered instanton solutions describing the birth of inflationary universes. His work on open inflation forms the basis of the widely discussed multiverse paradigm. With Paul Steinhardt, he developed an alternative, cyclic model for cosmology, whose predictions are so far in agreement with all observational tests. Among his many honours, Turok was awarded Sloan and Packard Fellowships and the James Clerk Maxwell medal of the Institute of Physics (UK). He is a Canadian Institute for Advanced Research (CIFAR) Fellow in Cosmology and Gravity and a Senior Fellow of Massey College in the University of Toronto. In 2012, Turok delivered the CBC Massey Lectures. The lectures were published as *The Universe Within*, a bestseller which won the 2013 Lane Anderson Award, Canada's top prize for popular science writing. Born in South Africa, Turok founded the African Institute for Mathematical Sciences (AIMS) in Cape Town in 2003. AIMS has since expanded to a network of four centres – in South Africa, Senegal, Ghana, and Cameroon – and has become Africa's most renowned institution for postgraduate training in mathematical science. For his scientific discoveries and his work founding and developing AIMS, Turok was awarded a TED Prize in 2008. He has also been recognized with awards from the World Summit on Innovation and Entrepreneurship (WSIE) and the World Innovation Summit on Education (WISE).

Dmitry Abanin (PhD Massachusetts Institute of Technology, 2008) joined Perimeter in 2012 from Harvard University, where he had been a postdoctoral fellow since 2011. Previously, he was a Research Scholar at the Princeton Center for Theoretical Science from 2008 to 2011. Abanin is a leading young condensed matter theorist whose research has focused on developing a theoretical understanding of Dirac materials, focusing on quantum transport of charge and spin and finding new ways of controlling their electronic properties. Some of his theoretical work has been experimentally confirmed by groups at Harvard University, University of Manchester, Columbia University, University of California, Riverside, the Max Planck Institute, and elsewhere.

Latham Boyle (PhD Princeton University, 2006) joined the Institute as a junior faculty member in 2010. From 2006 to 2009, he held a Canadian Institute for Theoretical Astrophysics (CITA) Postdoctoral Fellowship; he is also a Junior Fellow of the Canadian Institute for Advanced Research (CIFAR). Boyle has studied what gravitational wave measurements can reveal about the universe's beginning; with Paul Steinhardt, he derived 'inflationary bootstrap relations' that − if confirmed observationally − would provide compelling support for the theory of primordial inflation. He co-developed a simple algebraic technique for understanding black hole mergers and recently constructed the theory of 'porcupines':

networks of low-frequency gravitational wave detectors that function together as gravitational wave telescopes.

Freddy Cachazo (PhD Harvard University, 2002) has been a faculty member at Perimeter since 2005. From 2002 to 2005, he was a Member of the School of Natural Sciences at the Institute for Advanced Study in Princeton. Cachazo is one of the world's leading experts in the study and computation of scattering amplitudes in quantum chromodynamics (QCD) and N=4 super Yang-Mills (MSYM) theories. His many honours include an Early Researcher Award (2007), the Gribov Medal of the European Physical Society (2009), the Rutherford Memorial Medal in Physics from the Royal Society of Canada (2011), and the Herzberg Medal (2012).

Bianca Dittrich (PhD Max Planck Institute for Gravitational Physics, 2005) joined Perimeter's faculty in January 2012 from the Albert Einstein Institute in Potsdam, Germany, where she led the Max Planck Research Group "Canonical and Covariant Dynamics of Quantum Gravity." Dittrich's research focuses on the construction and examination of quantum gravity models. Among other important findings, she has provided a computational framework for gauge invariant observables in canonical general relativity. In 2007, Dittrich received the Otto Hahn Medal of the Max Planck Society, which recognizes outstanding young scientists.

Laurent Freidel (PhD L'École Normale Supérieure de Lyon, 1994) joined Perimeter Institute in September 2006. Freidel is a mathematical physicist who has made many notable contributions in the field of quantum gravity; he possesses outstanding knowledge of a wide range of areas including integrable systems, topological field theories, 2D conformal field theory, and quantum chromodynamics. Freidel has held positions at Pennsylvania State University and L'École Normale Supérieure and has been a member of France's Centre National de la Recherche Scientifique (CNRS) since 1995. Freidel is also the recipient of several awards, including two ACI-Blanche grants in France.

Davide Gaiotto (PhD Princeton University, 2004) joined Perimeter in May 2012. Previously, he was a postdoctoral fellow at Harvard University from 2004 to 2007 and a long-term Member at the Institute for Advanced Study in Princeton from 2007 to 2012. Gaiotto works in the area of strongly coupled quantum fields and has already made several major conceptual advances that have potentially revolutionary implications. His honours include the Gribov Medal of the European Physical Society (2011) and a New Horizons in Physics Prize from the Fundamental Physics Prize Foundation (2012).

Jaume Gomis (PhD Rutgers University, 1999) joined Perimeter Institute in 2004, declining a European Young Investigator Award by the European Science Foundation to do so. Prior to that, he worked at the California Institute of Technology as a Postdoctoral Scholar and as the Sherman Fairchild Senior Research Fellow. His main areas of expertise are string theory and quantum field theory. In 2009, Gomis was awarded an Early Researcher Award for a project aimed at developing new techniques for describing quantum phenomena in nuclear and particle physics.

Daniel Gottesman (PhD California Institute of Technology, 1997) joined Perimeter's faculty in 2002. From 1997 to 2002, he held postdoctoral positions at the Los Alamos National Laboratory, Microsoft Research, and the University of California, Berkeley (as a long-term CMI Prize Fellow for the Clay

Mathematics Institute). Gottesman has made seminal contributions which continue to shape the field of quantum information science through his work on quantum error correction and quantum cryptography. He has published over 40 papers, which have attracted well over 4,000 citations to date. He is also a Senior Fellow in the Quantum Information Processing program of the Canadian Institute for Advanced Research (CIFAR) and a Fellow of the American Physical Society (APS).

Lucien Hardy (PhD University of Durham, 1992) joined Perimeter's faculty in 2002, having previously held research and lecturing positions at various European universities including the University of Oxford, Sapienza University of Rome, the University of Durham, the University of Innsbruck, and the National University of Ireland. In 1992, he found a very simple proof of non-locality in quantum theory which has become known as Hardy's theorem. He currently works on characterizing quantum theory in terms of operational postulates and applying the insights obtained to the problem of quantum gravity.

Luis Lehner (PhD University of Pittsburgh, 1998) began a joint appointment with Perimeter and the University of Guelph in 2009 and became a full-time faculty member at Perimeter in 2012. He previously held postdoctoral fellowships at the University of Texas at Austin and the University of British Columbia, and he was a member of Louisiana State University's faculty from 2002 to 2009. Lehner's many honours include the Honor Prize from the National University of Cordoba, Argentina, a Mellon pre-doctoral fellowship, the CGS/UMI outstanding dissertation award, and the Nicholas Metropolis award. He has been a PIMS fellow, a CITA National Fellow, and a Sloan Research Fellow, and he is currently a Fellow of the Institute of Physics, the American Physical Society, the International Society for General Relativity and Gravitation, and the Canadian Institute for Advanced Research (CIFAR) in the Cosmology and Gravity program.

Robert Myers (PhD Princeton University, 1986) is one of the leading theoretical physicists working in string theory in Canada. After attaining his PhD, he was a postdoctoral researcher at the Institute for Theoretical Physics at the University of California, Santa Barbara, and a Professor of Physics at McGill University, before moving to Perimeter in 2001. He has made seminal contributions to our understanding of black hole microphysics and D-branes. Among Myers' many honours, he has received the Herzberg Medal (1999), the CAP-CRM Prize (2005), and the Vogt Medal (2012). He is also a Fellow of both the Royal Society of Canada and the Cosmology and Gravity program of the Canadian Institute for Advanced Research (CIFAR).

Philip Schuster (PhD Harvard University, 2007) joined Perimeter's faculty in 2010. He was a Research Associate at SLAC National Accelerator Laboratory from 2007 to 2010. Schuster's area of specialty is particle theory, with an emphasis on physics beyond the Standard Model. He has close ties to experiment and has investigated various theories that may be discovered at experiments at the Large Hadron Collider (LHC) at CERN. With members of the Compact Muon Solenoid (CMS) experiment at the LHC, he developed methods to characterize potential new physics signals and null results in terms of simplified models, facilitating more robust theoretical interpretations of data. He is also a co-spokesperson for the APEX collaboration at the Thomas Jefferson National Accelerator Facility in Virginia.

Kendrick Smith (PhD University of Chicago, 2007) joined Perimeter in September 2012 from Princeton University, where he was the Lyman P. Spitzer Postdoctoral Fellow since 2009. Prior to that, he held the PPARC Postdoctoral Fellowship at the University of Cambridge from 2007 to 2009. Smith is a cosmologist with a foot in the worlds of both theory and observation. He is a member of several experimental teams, including the WMAP collaboration, which won the 2012 Gruber Cosmology Prize, as well as QUIET and the Planck collaboration. Smith has achieved several landmark results, including the first detection of gravitational lensing in the cosmic microwave background (CMB) radiation. He is currently on a one-year leave of absence to participate in the start-up phase of the major Hyper-Suprime Cam project at the Hawaii-based Subaru telescope, after which he will bring full data rights to Perimeter. Smith holds a second PhD in mathematics from the University of Michigan.

Lee Smolin (PhD Harvard University, 1979) is one of Perimeter Institute's founding faculty members. Prior to joining Perimeter, Smolin held research positions at the Institute for Advanced Study, the Institute for Theoretical Physics at the University of California, Santa Barbara, the Enrico Fermi Institute at the University of Chicago, Yale University, Syracuse University, and Pennsylvania State University. Smolin's research is centred on the problem of quantum gravity, with particular focus on loop quantum gravity and deformed special relativity, though his contributions span many areas. His papers have generated over 6,400 citations to date and he has written four non-technical books. Smolin's many honours include the Majorana Prize (2007), the Klopsteg Memorial Award (2009), and election as a Fellow of both the American Physical Society and the Royal Society of Canada.

Robert Spekkens (PhD University of Toronto, 2001) joined Perimeter's faculty in 2008, after holding a postdoctoral fellowship at Perimeter and an International Royal Society Fellowship at the University of Cambridge. His research is focused upon identifying the conceptual innovations that distinguish quantum theories from classical theories and investigating their significance for axiomatization, interpretation, and the implementation of various information-theoretic tasks. Spekkens is a previous winner of the Birkhoff-von Neumann Prize of the International Quantum Structures Association.

Natalia Toro (PhD Harvard University, 2007) joined Perimeter in 2010 after completing a postdoctoral fellowship at the Stanford Institute for Theoretical Physics. Toro has developed a framework for few-parameter models of possible new physics signals and has played a major role in integrating new techniques, called 'on-shell effective theories,' into the program of upcoming searches at the Compact Muon Solenoid experiment at the Large Hadron Collider (LHC) at CERN. She is an expert in the study of 'dark forces' that couple very weakly to ordinary matter and is co-spokesperson for APEX, an experiment searching for such forces at the Thomas Jefferson National Accelerator Facility.

Guifre Vidal (PhD University of Barcelona, 1999) joined Perimeter's faculty in 2011 from the University of Queensland in Brisbane, where he was an Australian Research Council Federation Fellow and Professor in the School of Mathematics and Physics. He did postdoctoral fellowships at the University of Innsbruck in Austria and the Institute for Quantum Information at the California Institute of Technology before joining the University of Queensland. Vidal works at the interface of quantum information and condensed matter physics, using tensor networks to compute the ground state of quantum many-body systems on a lattice and to issue a classification of the possible phases of quantum matter or fixed

points of the renormalization group flow. His past honours include a Marie Curie Fellowship, awarded by the European Union, and a Sherman Fairchild Foundation Fellowship.

Pedro Vieira (PhD École Normale Supérieure Paris and the Theoretical Physics Center at University of Porto, 2008) joined Perimeter in 2009 from the Max Planck Institute for Gravitational Physics (Albert Einstein Institute), where he was a Junior Scientist from 2008 to 2009. Vieira's research concerns the development of new mathematical techniques for gauge and string theories, ultimately aiming at the solution of a realistic four-dimensional gauge theory. His research interests also include the related areas of the AdS/CFT correspondence and theoretical calculations of scattering amplitudes. "Y-system for scattering amplitudes," a paper by Vieira and his collaborators, won the 2012 Best Paper Prize from the Institute of Physics (IOP) and the Editorial Board of *Journal of Physics A*. He also won an Early Researcher Award in 2012.

Xiao-Gang Wen (PhD Princeton University, 1987) joined Perimeter's faculty in May 2012. Widely recognized as one of the world's leaders in condensed matter theory, he pioneered the new paradigm of quantum topological order, used to describe phenomena from superconductivity to fractionally charged particles, and he has invented many new mathematical formalisms. Wen authored the textbook *Quantum Field Theory of Many-body Systems: From the Origin of Sound to an Origin of Light and Electrons*. He was previously a Distinguished Moore Scholar at the California Institute of Technology and the Cecil and Ida Green Professor of Physics at the Massachusetts Institute of Technology, as well as one of Perimeter's own Distinguished Visiting Research Chairs. He is also a Fellow of the American Physical Society.

Associate Faculty

Niayesh Afshordi (PhD Princeton University, 2004) is jointly appointed with the University of Waterloo. He was the Institute for Theory and Computation Fellow at the Harvard-Smithsonian Center for Astrophysics from 2004 to 2007 and a Distinguished Research Fellow at Perimeter Institute from 2008 to 2009. Afshordi began his appointment as an associate faculty member in 2010. He specializes in interdisciplinary problems in fundamental physics, astrophysics, and cosmology. In 2010, he was awarded a Discovery Accelerator Supplement from the Natural Sciences and Engineering Research Council of Canada (NSERC).

Avery Broderick (PhD California Institute of Technology, 2004) began a joint appointment with Perimeter and the University of Waterloo in 2011. He previously held postdoctoral positions at the Institute for Theory and Computation at the Harvard-Smithsonian Center for Astrophysics (2004-07) and the Canadian Institute for Theoretical Astrophysics (2007-11). Broderick is an astrophysicist with broad research interests, ranging from how stars form to the extreme physics in the vicinity of white dwarfs, neutron stars, and black holes. He has recently been part of an international effort to produce and interpret horizon-resolving images of supermassive black holes, studying how black holes accrete matter, launch the ultra-relativistic outflows observed, and probe the nature of gravity in their vicinity.

Alex Buchel (PhD Cornell University, 1999) is jointly appointed with Western University. Before joining Perimeter's faculty in 2003, he held research positions at the Institute for Theoretical Physics at the University of California, Santa Barbara (1999-2002), and the Michigan Center for Theoretical Physics at the University of Michigan (2002-03). Buchel's research efforts focus on understanding the quantum properties of black holes and the origin of our universe, as described by string theory, as well as developing analytical tools that could shed new light on strong interactions of subatomic particles. In 2007, he was awarded an Early Researcher Award from Ontario's Ministry of Research and Innovation.

Cliff Burgess (PhD University of Texas at Austin, 1985) joined Perimeter's faculty as an associate member in 2004 and was jointly appointed to McMaster University's faculty in 2005. Prior to that, he was a Member in the School of Natural Sciences at the Institute for Advanced Study in Princeton and a faculty member at McGill University. Over two decades, Burgess has applied the techniques of effective field theory to high energy physics, nuclear physics, string theory, early universe cosmology, and condensed matter physics. With collaborators, he developed leading string theoretic models of inflation that provide its most promising framework for experimental verification. Burgess' recent honours include a Killam Fellowship, Fellowship of the Royal Society of Canada, and the CAP-CRM Prize in Theoretical and Mathematical Physics.

David Cory (PhD Case Western Reserve University, 1987) is jointly appointed with the Institute for Quantum Computing and the University of Waterloo. He held research positions at the University of Nijmegen in The Netherlands, the National Research Council at the Naval Research Laboratory in Washington, D.C., and the Massachusetts Institute of Technology. He also led research and development activities in nuclear magnetic resonance at Bruker Instruments. Since 1996, Cory has been exploring the experimental challenges of building small quantum processors based on nuclear spins, electron spins,

neutrons, persistent current superconducting devices, and optics. In 2010, he was named the Canada Excellence Research Chair in Quantum Information Processing. Cory chairs the advisory committee for the Quantum Information Processing program at the Canadian Institute for Advanced Research (CIFAR).

Matthew Johnson (PhD University of California, Santa Cruz, 2007) began a joint appointment with Perimeter and York University in August 2012. Prior to that, he was a Moore Postdoctoral Scholar at the California Institute of Technology and a postdoctoral researcher at Perimeter. Johnson is a cosmologist, whose interdisciplinary research seeks to understand how the universe began, how it evolved, and where it is headed. To this end, he designs data analysis algorithms to confront fundamental theory with observations of the cosmic microwave background radiation. In 2012, Johnson was awarded a New Frontiers in Astronomy and Cosmology grant from the University of Chicago and the John Templeton Foundation.

Raymond Laflamme (PhD University of Cambridge, 1988) is a founding faculty member of Perimeter Institute and founding Director of the Institute for Quantum Computing, where he is jointly appointed. He held research positions at the University of British Columbia and Peterhouse College, University of Cambridge, before moving to the Los Alamos Research Laboratory in 1992, where his interests shifted from cosmology to quantum computing. Since the mid-1990s, Laflamme has elucidated theoretical approaches to quantum error correction and in turn implemented some in experiments. Laflamme has been Director of the Quantum Information Processing program at the Canadian Institute for Advanced Research (CIFAR) since 2003. He is a Fellow of CIFAR, the American Physical Society, and the American Association for the Advancement of Science, and holds the Canada Research Chair in Quantum Information. With colleagues, he founded Universal Quantum Devices, a start-up commercializing spin-offs of quantum research.

Sung-Sik Lee (PhD Pohang University of Science and Technology, 2000) joined Perimeter in 2011 in a joint appointment with McMaster University, where he is an Associate Professor. He previously worked as a postdoctoral researcher at the Pohang University of Science and Technology, the Massachusetts Institute of Technology, and the Kavli Institute for Theoretical Physics at the University of California, Santa Barbara. Lee's research focuses on strongly interacting quantum many-body systems using quantum field theory, as well as the intersections between condensed matter and high energy physics. His recent work has included using gauge theory as a lens through which to examine the phenomenon of fractionalization, efforts to apply the AdS/CFT correspondence from string theory to quantum chromodynamics and condensed matter, and building a non-perturbative approach to understanding unconventional metallic states of matter.

Roger Melko (PhD University of California, Santa Barbara, 2005) joined Perimeter in September 2012, while retaining his appointment with the University of Waterloo, where he has been since 2007. Prior to that, he was a Wigner Fellow at Oak Ridge National Laboratory (2005-07). Melko is a condensed matter theorist who develops new computational methods and algorithms to study strongly correlated many-body systems, focusing on emergent phenomena, ground state phases, phase transitions, quantum criticality, and entanglement. Among his honours, he has received an Early Researcher Award, the International Union of Pure and Applied Physics Young Scientist Prize in Computational Physics from the

Council on Computational Physics, and the Canada Research Chair in Computational Quantum Many-Body Physics (Tier 2).

Michele Mosca (DPhil University of Oxford, 1999) is jointly appointed with the Institute for Quantum Computing at the University of Waterloo. He is a founding member of Perimeter Institute, as well as co-founder and Deputy Director of the Institute for Quantum Computing. Mosca has made major contributions to the theory and practice of quantum information processing, including several of the first implementations of quantum algorithms and fundamental methods for performing reliable computations with untrusted quantum apparatus. His current research interests include quantum algorithms and complexity, and the development of cryptographic tools that will be safe against quantum technologies. Mosca's numerous academic honours include Canada's Top 40 Under 40 award (2010), the Premier's Research Excellence Award (2000-05), Fellow of the Canadian Institute for Advanced Research (CIFAR) since 2010, Canada Research Chair in Quantum Computation (2002-12), and University Research Chair at the University of Waterloo (2012-present).

Maxim Pospelov (PhD Budker Institute of Nuclear Physics, 1994) is jointly appointed with the University of Victoria and became an Associate Faculty member at Perimeter in 2004. He previously held research positions at the University of Quebec at Montreal, the University of Minnesota, McGill University, and the University of Sussex. Pospelov works in the areas of particle physics and cosmology.

Itay Yavin (PhD Harvard University, 2006) began a joint appointment with Perimeter and McMaster University in 2011. Previously, he was a Research Associate at Princeton University and a James Arthur Postdoctoral Fellow at New York University. Yavin's research focuses on particle physics and the search for physics beyond the Standard Model. In particular, he is interested in the origin of electroweak symmetry breaking and the nature of dark matter. Most recently, he has worked on interpreting puzzling data coming from experiments looking for dark matter in the lab.

Appendix C: Distinguished Visiting Research Chairs

Dorit Aharonov is a Professor in the Department of Computer Science and Engineering at Hebrew University in Jerusalem. She has made major contributions to the theoretical foundations of quantum computation, in particular in the context of understanding and counteracting the effects of 'noisy' environments on delicate quantum systems performing computations, the identification of a quantum to classical phase transition in fault tolerant quantum computers, the development of new tools and approaches for the design of quantum algorithms, and the study of ground states of many-body quantum Hamiltonians for various classes of Hamiltonians, from a computational complexity point of view. In 2006, she was awarded the Krill Prize for excellence in scientific research.

Yakir Aharonov is a professor of theoretical condensed matter physics at Chapman University and Professor Emeritus at Tel Aviv University. He has made seminal contributions in quantum mechanics, relativistic quantum field theories, and interpretations of quantum mechanics. In 1998, he received the prestigious Wolf Prize for his 1959 co-discovery of the Aharonov-Bohm effect. In 2010, US President Barack Obama awarded Professor Aharonov the National Medal of Science, the highest scientific honour bestowed by the United States government.

Nima Arkani-Hamed of the Institute for Advanced Study is one of the world's leading particle physicists, a previous long-term visitor at PI, and a lecturer for the Perimeter Scholars International master's program. Professor Arkani-Hamed has developed theories on emergent extra dimensions, 'little Higgs theories', and recently proposed new models that can be tested using the Large Hadron Collider (LHC) at CERN in Switzerland. In 2012, he was one of the inaugural winners of the Fundamental Physics Prize.

James Bardeen is an Emeritus Professor of Physics at the University of Washington in Seattle. He has made major contributions in general relativity and cosmology, including the formulation, with Stephen Hawking and Brandon Carter, of the laws of black hole mechanics, and the development of a gauge-invariant approach to cosmological perturbations and the origin of large-scale structure in the present universe from quantum fluctuations during an early epoch of inflation. His recent research focuses on improving calculations of the generation of gravitational radiation from merging black hole and neutron star binaries by formulating the Einstein equations on asymptotically null constant mean curvature hypersurfaces. This makes possible numerical calculations with an outer boundary at future null infinity, where waveforms can be read off directly, without any need for extrapolation. Dr. Bardeen received his PhD from Caltech under the direction of Richard Feynman.

Ganapathy Baskaran is an Emeritus Professor at the Institute of Mathematical Sciences, Chennai in India, where he recently founded the Quantum Science Centre. He has made important contributions to the field of strongly correlated quantum matter. His primary research focus is novel emergent quantum phenomena in matter, including biological ones. He is well known for his contributions to the theory of high temperature superconductivity and for discovering emergent gauge fields in strongly correlated electron systems. He predicted p-wave superconductivity in Sr_2RuO_4, a system believed to support Majorana fermion mode, which is a popular qubit for topological quantum computation. In recent work, he predicted room temperature superconductivity in optimally doped graphene. From 1976 to 2006, Dr.

Baskaran contributed substantially to the Abdus Salam International Centre for Theoretical Physics in Trieste, Italy. He is a past recipient of the S.S. Bhatnagar Award from the Indian Council of Scientific and Industrial Research (1990); the Alfred Kasler ICTP Prize (1983); Fellowships of the Indian Academy of Sciences (1988), the Indian National Science Academy (1991), and the Third World Academy of Sciences (2008); and the Distinguished Alumni Award of the Indian Institute of Science, Bangalore (2008).

Juan Ignacio Cirac, Director of the Theory Division of the Max Planck Institute of Quantum Optics in Germany, is a leading quantum information theorist whose group received the 2009 Carl Zeiss Research Award. His research aims to characterize quantum phenomena and to develop a new theory of information based on quantum mechanics, work which may ultimately lead to the development of quantum computers.

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. He has over 160 publications.

S. James Gates is the John S. Toll Professor and Director for the Center for String and Particle Theory at the University of Maryland, College Park. Dr. Gates' research has made numerous contributions to supersymmetry, supergravity, and superstring theory, including the introduction of complex geometries with torsion (a new contribution in the mathematical literature), and the suggestion of models of superstring theories that exit purely as four-dimensional constructs similar to the standard model of particle physics. He has won the Public Understanding & Technology Award from the American Association for the Advancement of Science (AAAS), the Klopsteg Award from the American Association of Physics Teachers (AAPT), and the US National Medal of Science. Dr. Gates is a Fellow of both AAAS and the American Physical Society, and a past President of the National Society of Black Physicists. In 2011, he was elected to the American Academy of Arts and Sciences. He serves on the US President's Council of Advisors on Science and Technology, the Maryland State Board of Education, the Board of Directors of the Fermi National Laboratory, and the Board of Trustees for the Society for Science and the Public.

Alexander Goncharov is a Professor in the Department of Mathematics at Yale University. Prior to joining Yale's faculty, he was a professor at Brown University, the Max Planck Institute for Mathematics, and the Massachusetts Institute of Technology. Goncharov's research primarily concerns mathematical physics, including arithmetic algebraic geometry and representation theory. He is known for the Goncharov conjecture, which suggests that the cohomology of certain motivic complexes coincides with pieces of K-groups. In 1992, Goncharov won the European Mathematical Society Prize.

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-perturbative

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).

Stephen Hawking is the Director of Research at the Centre for Theoretical Cosmology at the University of Cambridge. From 1979 to 2009, he was the Lucasian Professor of Mathematics in the Department of Applied Mathematics and Theoretical Physics at Cambridge. In his work, Professor Hawking seeks to better understand the basic laws which govern the universe. With Roger Penrose, he showed that Einstein's theory of general relativity implied space and time would have a beginning in the big bang and an end in black holes. Professor Hawking is known for his popular works on science, including *A Brief History of Time*, which is the most popular scientific book of all time and has sold over 30 million copies worldwide. Professor Hawking has 12 honorary degrees, was made a Companion of the British Empire in 1982, and was made a Companion of Honour in 1989. He is the recipient of many awards, medals, and prizes, and is a Fellow of The Royal Society and a Member of the US National Academy of Sciences.

Patrick Hayden is a Professor of Physics at Stanford University. He is a leader in quantum information science who has contributed greatly to our understanding of the absolute limits that quantum mechanics places on information processing, and how to exploit quantum effects for computing and communication. He has also made some key insights on the relationship between black holes and information theory. Among Dr. Hayden's honours, he is a past Sloan Research Fellow and Rhodes Scholar. He also held the Canada Research Chair in the Physics of Information at McGill University prior to joining Stanford.

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*.

Leo Kadanoff is a theoretical physicist and applied mathematician based at the James Franck Institute at the University of Chicago. He is a pioneer of complexity theory and has made important contributions to research in the properties of matter, the development of urban areas, statistical models of physical systems, and the development of chaos in simple mechanical and fluid systems. He is best known for the development of the concepts of 'scale invariance' and 'universality' as they are applied to phase transitions. More recently, he has been involved in the understanding of singularities in fluid flow. Among Dr. Kadanoff's many honours, he is a past recipient of the US National Medal of Science, the Grande Medaille d'Or of the Académie des Sciences de l'Institut de France, the Wolf Foundation Prize,

the Boltzmann Medal of the International Union of Pure and Applied Physics, and the Centennial Medal of Harvard University. He is also a past President of the American Physical Society.

Adrian Kent is a Reader in Quantum Physics with the University of Cambridge. He has previously held positions as an Enrico Fermi Postdoctoral Fellow at the University of Chicago, a member of the Institute for Advanced Study, and a Royal Society University Research Fellow at the University of Cambridge. Prior to becoming a DVRC, Kent was an associate faculty member at Perimeter Institute. His research focuses on the foundations of physics, quantum cryptography, and quantum information theory, including the physics of decoherence, novel tests of quantum theory and alternative theories, and new applications of quantum information.

Renate Loll is a Professor of Theoretical Physics at the Institute for Mathematics, Astrophysics and Particle Physics of the Radboud University in Nijmegen, Netherlands. Her research centres on quantum gravity, the search for a consistent theory that describes the microscopic constituents of spacetime geometry and the quantum-dynamical laws governing their interaction. She has made major contributions to loop quantum gravity and, with her collaborators, has proposed a novel theory of quantum gravity via 'Causal Dynamical Triangulations'. Dr. Loll heads one of the largest research groups on non-perturbative quantum gravity worldwide and is the recipient of a prestigious personal VICI-grant of the Netherlands Organization for Scientific Research.

Ramesh Narayan is the Thomas Dudley Cabot Professor of the Natural Sciences at Harvard University. He is an astrophysicist who has won international renown for his research on black holes. Narayan has also carried out research in a number of other areas of theoretical astrophysics, including accretion disks, gravitational lensing, gamma-ray bursts, and neutron stars. He is a Fellow of the Royal Society of London and the American Association for the Advancement of Science, and a member of the International Astronomical Union and the American Astronomical Society.

Sandu Popescu is a Professor of Physics at the H.H. Wills Physics Laboratory at the University of Bristol and a member of the Bristol Quantum Information and Computation Group. He has made numerous contributions to quantum theory, ranging from the very fundamental to the design of practical experiments (such as the first teleportation experiment), to patentable commercial applications. His investigations into the nature of quantum behaviour, with particular focus on quantum non-locality, led him to discover some of the central concepts in the emerging area of quantum information and computation. He is a past recipient of the Adams Prize (Cambridge) and the Clifford Patterson Prize of the Royal Society (UK).

Frans Pretorius is a Professor of Physics at Princeton University. His primary field of research is general relativity, specializing in numerical solution of the field equations. His work has included studies of gravitational collapse, black hole mergers, cosmic singularities, higher dimensional gravity, models of black hole evaporation, and using gravitational wave observations to test the dynamical, strong-field regime of general relativity. He also designs algorithms to efficiently solve the equations in parallel on large computer clusters, and software to manipulate and visualize the simulation results. Among his honours, in 2007, Dr. Pretorius was awarded a Sloan Research Fellowship and was the 2010 recipient of

the Aneesur Rahman Prize for Computational Physics of the American Physical Society. He is also a Scholar in the Canadian Institute for Advanced Research (CIFAR) Cosmology and Gravity program.

Subir Sachdev of Harvard University has made prolific contributions to quantum condensed matter physics, including research on quantum phase transitions and their application to correlated electron materials like high temperature superconductors. His 1999 book, *Quantum Phase Transitions*, has been described as "required reading for any budding theorist."

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).

Eva Silverstein is a Professor of Physics at Stanford University and the SLAC National Accelerator Laboratory. Dr. Silverstein's major contributions include predictive new mechanisms for inflationary cosmology, which helped motivate a more systematic understanding of the process and the role of UV-sensitive quantities in observational cosmology; mechanisms for singularity resolution in string theory; a novel duality in string theory between extra dimensions and negative curvature; extensions of the AdS/CFT correspondence to more realistic field theories (with applications to particle physics and condensed matter model building) and to landscape theories; and simple mechanisms for stabilizing the extra dimensions of string theory. She is a former MacArthur Fellow and past recipient of a Sloan Research Fellowship.

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.

Paul Steinhardt is the Albert Einstein Professor in Science and Director of the Princeton Center for Theoretical Science at Princeton University. Dr. Steinhardt is a Fellow in the American Physical Society (APS) and a member of the National Academy of Sciences. He shared the P.A.M. Dirac Medal from the International Centre for Theoretical Physics for the development of the inflationary model of the universe, and the Oliver E. Buckley Prize of the APS for his contributions to the theory of quasicrystals. His research interests include particle physics, astrophysics, cosmology, and condensed matter physics. Recently, with Neil Turok, he has developed a cyclic model for cosmology, according to which the big

bang is explained as a collision between two 'brane-worlds' in M-theory. In addition to his continued research on inflationary and cyclic cosmology, Steinhardt has been one of the developers of a new class of disordered 'hyperuniform' photonic materials with complete bandgaps, and he conducted a systematic search for natural quasicrystals that has culminated in discovering the first known example. He is currently organizing an expedition to Far Eastern Russia to find more samples and study the local geology where they are found.

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.

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).

Leonard Susskind is the Felix Bloch Professor of Theoretical Physics at Stanford University. Regarded as one of the fathers of string theory, Professor Susskind has also made seminal contributions to particle physics, black hole theory, and cosmology. His current research centres upon questions in theoretical particle physics, gravitational physics, and quantum cosmology.

Gerard 't Hooft is a Professor at the Institute for Theoretical Physics at Utrecht University. He shared the 1999 Nobel Prize in Physics with Martinus J.G. Veltman "for elucidating the quantum structure of electroweak interactions." His research interests include gauge theories in elementary particle physics, quantum gravity and black holes, and fundamental aspects of quantum physics. In addition to being a Nobel laureate, Dr. 't Hooft is a past winner of the Wolf Prize, the Lorentz Medal, the Franklin Medal, and the High Energy Physics Prize from the European Physical Society, among other honours. He is a member of the Royal Netherlands Academy of Arts and Sciences (KNAW) and is a foreign member of many other science academies, including the French Académie des Sciences, the National Academy of Sciences (US), and the Institute of Physics (UK). Dr. 't Hooft's present research concentrates on the question of nature's dynamical degrees of freedom at the tiniest possible scales. In his latest model, local conformal invariance is a spontaneously broken symmetry, which may have very special implications for the interactions between elementary particles.

Senthil Todadri is an Associate Professor of Physics at the Massachusetts Institute of Technology (MIT). Dr. Todadri's research interests are in condensed matter theory. Specifically, he is working to develop a theoretical framework to describe the behaviour of electronic quantum matter in circumstances in which individual electrons have no integrity. A prime example is the quest for a replacement for the Landau theory of Fermi liquids that describes many metals extremely successfully, but fails in a number of situations studied in modern experiments in condensed matter physics. He is a past Sloan Research Fellow and winner of a Research Innovation Award from the Research Corporation for Science Advancement.

William Unruh is a Professor of Physics at the University of British Columbia who has made seminal contributions to our understanding of gravity, black holes, cosmology, quantum fields in curved spaces, and the foundations of quantum mechanics, including the discovery of the Unruh effect. His investigations into the effects of quantum mechanics of the earliest stages of the universe have yielded many insights, including the effects of quantum mechanics on computation. Dr. Unruh was the first Director of the Cosmology and Gravity program at the Canadian Institute for Advanced Research (1985-1996). His many awards include the Rutherford Medal of the Royal Society of Canada (1982), the Herzberg Medal of the Canadian Association of Physicists (1983), the Steacie Prize from the National Research Council (1984), the Canadian Association of Physicists Medal of Achievement (1995), and the Canada Council Killam Prize (1996). He is an elected Fellow of the Royal Society of Canada, a Fellow of the American Physical Society, a Fellow of the Royal Society of London, and a Foreign Honorary Member of the American Academy of Arts and Science.

Ashvin Vishwanath is an Associate Professor in the Department of Physics at the University of California, Berkeley. His primary field is condensed matter theory, with a focus on magnetism, superconductivity, and other correlated quantum phenomena in solids and cold atomic gases. Dr. Vishwanath is particularly interested in novel phenomena, such as topological phases of matter, non-fermi liquids, and quantum spin liquids. He has recently been interested in realizing Majorana and Weyl fermions in solids and in using concepts from quantum information, such as entanglement entropy, to characterize novel phases of matter. His past honours include a Sloan Research Fellowship (2004), the CAREER Award of the National Science Foundation (2007), the Outstanding Young Scientist Award of the American Chapter of Indian Physicists (2010), and the Simons Foundation Sabbatical Fellowship (2012).

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.

Steven White is a Professor in the Department of Physics at the University of California, Irvine. His primary research concerns condensed matter theory with an emphasis on numerical approaches for

strongly correlated magnetic and superconducting systems. In 1992, White invented the density matrix renormalization group (DMRG), a numerical variation technique for high accuracy calculations of the low energy physics of quantum many body systems. For his efforts, White has been recognized as a Fellow of the American Physical Society (1998) and the American Association for the Advancement of Science (2008). In 2003, he won the Aneesur Rahman Prize, the highest honour in the field of computational physics given by the American Physical Society.

Mark Wise is the John A. McCone Professor of High Energy Physics at the California Institute of Technology. He has conducted research in elementary particle physics and cosmology, and shared the 2001 Sakurai Prize for Theoretical Particle Physics for the development of the 'Heavy Quark Effective Theory' (HQET), a mathematical formalism that enables physicists to make predictions about otherwise intractable problems in the theory of the strong interactions of quarks. He has also published work on mathematical models for finance and risk assessment. Dr. Wise is a past Sloan Research Fellow, a Fellow of the American Physical Society, and a member of the American Academy of Arts and Sciences and of the National Academy of Sciences.

Appendix D: Affiliate Members

Name	Institution	Research Area
Ian Affleck	University of British Columbia	Condensed Matter
Arif Babul	University of Victoria	Cosmology
Leslie Ballentine	Simon Fraser University	Quantum Foundations
Richard Bond	University of Toronto/Canadian Institute for Theoretical Astrophysics (CITA)	Cosmology
Ivan Booth	Memorial University	Strong Gravity
Vincent Bouchard	University of Alberta	Quantum Fields and Strings
Robert Brandenberger	McGill University	Cosmology
Gilles Brassard	University of Montreal	Quantum Information
Anne Broadbent	University of Waterloo/Institute for Quantum Computing (IQC)	Quantum Information
Anton Burkov	University of Waterloo	Condensed Matter
Bruce Campbell	Carleton University	Particle Physics
Benoit Charbonneau	St. Jerome's University	Quantum Fields and Strings
Jeffrey Chen	University of Waterloo	Condensed Matter
Andrew Childs	University of Waterloo/IQC	Quantum Information
Matthew Choptuik	University of British Columbia	Strong Gravity
Dan Christensen	Western University	Quantum Gravity
Aashish Clerk	McGill University	Condensed Matter
James Cline	McGill University	Cosmology, Particle Physics
Alan Coley	Dalhousie University	Strong Gravity
Andrzej Czarnecki	University of Alberta	Particle Physics

Name	Institution	Research Area
Saurya Das	University of Lethbridge	Quantum Gravity
Arundhati Dasgupta	University of Lethbridge	Quantum Gravity
Keshav Dasgupta	McGill University	Quantum Fields and Strings
Rainer Dick	University of Saskatchewan	Particle Physics
Joseph Emerson	University of Waterloo/IQC	Quantum Foundations
Valerio Faraoni	Bishop's University	Cosmology
James Forrest	University of Waterloo	Polymer Physics
Marcel Franz	University of British Columbia	Condensed Matter
Doreen Fraser	University of Waterloo	Philosophy
Andrew Frey	University of Winnipeg	Cosmology
Andrei Frolov	Simon Fraser University	Cosmology
Valeri Frolov	University of Alberta	Cosmology, Quantum Gravity
Jack Gegenberg	University of New Brunswick	Quantum Gravity
Ghazal Geshnizjani	University of Waterloo	Cosmology
Shohini Ghose	Wilfrid Laurier University	Quantum Information, Quantum Computation
Florian Girelli	University of Waterloo	Quantum Gravity, Applied Math
Stephen Godfrey	Carleton University	Particle Physics
Thomas Gregoire	Carleton University	Particle Physics
John Harnad	Concordia University	Mathematical Physics
Jeremy Heyl	University of British Columbia	Astrophysics
Bob Holdom	University of Toronto	Particle Physics
Michael Hudson	University of Waterloo	Cosmology

Name	Institution	Research Area
Viqar Husain	University of New Brunswick	Cosmology, Quantum Gravity
Thomas Jennewein	University of Waterloo/IQC	Quantum Information
Catherine Kallin	McMaster University	Condensed Matter
Joanna Karczmarek	University of British Columbia	Quantum Fields and Strings
Spiro Karigiannis	University of Waterloo	Mathematical Physics, Differential Geometry
Mikko Karttunen	University of Waterloo	Condensed Matter, Biology
Achim Kempf	University of Waterloo	Quantum Information
Yong-Baek Kim	University of Toronto	Condensed Matter
David Kribs	University of Guelph	Quantum Information
Hari Kunduri	Memorial University	Strong Gravity
Gabor Kunstatter	University of Winnipeg	Quantum Gravity, Quantum Mechanics
Kayll Lake	Queen's University	Strong Gravity
Debbie Leung	University of Waterloo	Quantum Information
Randy Lewis	York University	Particle Physics
Hoi-Kwong Lo	University of Toronto	Quantum Information
Michael Luke	University of Toronto	Particle Physics
Adrian Lupascu	University of Waterloo/IQC	Quantum Information
Norbert Lutkenhaus	University of Waterloo/IQC	Quantum Information
A. Hamed Majedi	University of Waterloo/IQC	Nanotechnology
Alexander Maloney	McGill University	Quantum Fields and Strings
Robert Mann	University of Waterloo	Quantum Fields and Strings, Quantum Gravity
Gerry McKeon	Western University	Particle Physics

Name	Institution	Research Area
Brian McNamara	University of Waterloo	Cosmology
Roger Melko	University of Waterloo	Condensed Matter
Volodya Miransky	Western University	Quantum Information
Guy Moore	McGill University	Particle Physics
Ruxandra Moraru	University of Waterloo	Mathematical Physics, Pure Math
David Morrissey	TRIUMF Canada	Particle Physics
Norman Murray	University of Toronto/CITA	Astrophysics
Wayne Myrvold	Western University	Philosophy
Julio Navarro	University of Victoria	Cosmology
Ashwin Nayak	University of Waterloo	Quantum Information
Elisabeth Nicol	University of Guelph	Condensed Matter
Don Page	University of Alberta	Cosmology
Prakash Panangaden	McGill University	Quantum Foundations
Arun Paramekanti	University of Toronto	Condensed Matter
Manu Paranjape	University of Montreal	Particle Physics
Amanda Peet	University of Toronto	Quantum Foundations, Quantum Fields and Strings
Ue-Li Pen	University of Toronto/CITA	Cosmology
Alexander Penin	University of Alberta	Condensed Matter, Particle Physics
Tamar Pereg-Barnea	McGill University	Condensed Matter
Harald Pfeiffer	University of Toronto/CITA	Strong Gravity
Marco Piani	University of Waterloo/IQC	Quantum Information
Levon Pogosian	Simon Fraser University	Cosmology

Name	Institution	Research Area
Dmitri Pogosyan	University of Alberta	Cosmology
Eric Poisson	University of Guelph	Strong Gravity
Erich Poppitz	University of Toronto	Particle Physics
David Poulin	University of Sherbrooke	Quantum Foundations
Robert Raussendorf	University of British Columbia	Quantum Information
Ben Reichardt	University of Waterloo	Quantum Information
Kevin Resch	University of Waterloo/IQC	Quantum Information
Adam Ritz	University of Victoria	Particle Physics
Moshe Rozali	University of British Columbia	Quantum Fields and Strings
Barry Sanders	University of Calgary	Quantum Information
Veronica Sanz-Gonzalez	York University	Particle Physics, High Energy Physics
Kristin Schleich	University of British Columbia	Strong Gravity
Achim Schwenk	TRIUMF Canada	Particle Physics
Douglas Scott	University of British Columbia	Cosmology
Sanjeev Seahra	University of New Brunswick	Cosmology, Quantum Gravity
Peter Selinger	Dalhousie University	Mathematical Physics
Gordon Semenoff	University of British Columbia	Quantum Fields and Strings
John Sipe	University of Toronto	Condensed Matter, Quantum Foundations
Philip Stamp	University of British Columbia	Cosmology
Aephraim Steinberg	University of Toronto	Quantum Information
Alain Tapp	University of Montreal	Quantum Information
James Taylor	University of Waterloo	Cosmology

Name	Institution	Research Area
Andre-Marie Tremblay	University of Sherbrooke	Condensed Matter
Mark Van Raamsdonk	University of British Columbia	Quantum Fields and Strings
Johannes Walcher	McGill University	Quantum Fields and Strings
Mark Walton	University of Lethbridge	Quantum Fields and Strings
John Watrous	University of Waterloo	Quantum Information
Steve Weinstein	University of Waterloo	Quantum Foundations
Lawrence Widrow	Queen's University	Astrophysics
Frank Wilhelm-Mauch	University of Waterloo/IQC	Condensed Matter
Don Witt	University of British Columbia	Particle Physics, Quantum Fields and Strings
Bei Zeng	University of Guelph	Quantum Information

Appendix E: Board of Directors

Mike Lazaridis, O.C., O.Ont., Chair, is the Founder of BlackBerry (formerly Research In Motion Limited) and recently founded the Quantum Valley Investment Fund to provide financial and intellectual capital for the development and commercialization of quantum physics and quantum computing breakthroughs. A visionary, innovator, and engineer of extraordinary talent, he transformed the communications industry with the development of the BlackBerry®. He is the recipient of many technology and business awards, a Fellow of the Royal Society of Canada, and a recipient of both the Order of Ontario and the Order of Canada.

Cosimo Fiorenza, Vice Chair, is the Vice-President and General Counsel of the Infinite Potential Group. Previously, he spent approximately 20 years with major Toronto law firms, where he specialized in corporate tax. During his tenure on Bay Street, he advised some of Canada's largest corporations and biggest entrepreneurs on income tax and commercial matters with a focus on technology and international structure. Mr. Fiorenza helped establish and is a Founding Director of Perimeter Institute. In addition to his current role as Vice Chair, he is Co-Chair of the Perimeter Leadership Council and a member of the Perimeter Finance Committee. In these capacities, he regularly assists and supports Perimeter's management team in a variety of contexts including financial, legal, and advancement matters. Mr. Fiorenza is also a member of the Board of Directors of the Institute for Quantum Computing at the University of Waterloo. He holds a degree in Business Administration from Lakehead University and a law degree from the University of Ottawa. He was called to the Bar in Ontario in 1991.

Peter Godsoe, O.C., O.Ont., is the former Chairman & Chief Executive Officer of Scotiabank, from which he retired in March 2004. He holds a BSc in Mathematics and Physics from the University of Toronto, an MBA from the Harvard Business School, and is a CA and a Fellow of the Institute of Chartered Accountants of Ontario. Mr. Godsoe remains active through a wide range of corporate boards and non-profit directorships.

Kevin Lynch, P.C., O.C., is a distinguished former public servant with 33 years of service with the Government of Canada. Most recently, Dr. Lynch served as Clerk of the Privy Council, Secretary to the Cabinet, and Head of the Public Service of Canada. Prior roles included Deputy Minister of Finance, Deputy Minister of Industry, and Executive Director (Canada, Ireland, Caribbean) of the International Monetary Fund. He is presently the Vice-Chair of BMO Financial Group.

Steve MacLean recently stepped down as President of the Canadian Space Agency (CSA). A physicist by training, in 1983 he was selected as one of the first six Canadian astronauts and he has participated in missions on the Space Shuttles Columbia (1992) and Atlantis (2006) to the International Space Station. In addition to senior roles within the CSA and extensive experience with NASA and the International Space Station, he is a strong supporter of science literacy and child education.

Art McDonald has been the Director of the Sudbury Neutrino Observatory (SNO) experiment for over 20 years. He holds the Gordon and Patricia Gray Chair in Particle Astrophysics at Queen's University and

works on the new SNO+ and DEAP experiments at the international SNOLAB, researching an accurate measurement of neutrino mass and seeking to observe directly dark matter particles making up a large fraction of the universe. Professor McDonald has received numerous awards for his research, including the 2011 Henry Marshall Tory Medal from the Royal Society of Canada and the 2007 Benjamin Franklin Medal in Physics, alongside researcher Yoji Totsuka. He was named an Officer of the Order of Canada in 2007.

Barbara Palk recently retired as President of TD Asset Management Inc., one of Canada's leading money management firms, and as Senior Vice-President of TD Bank Financial Group. She is a Fellow of the Canadian Securities Institute, a CFA Charterholder, and a member of both the Toronto Society of Financial Analysts and the Institute of Corporate Directors. Ms. Palk is Chair of the Board of Queen's University and a member of the Boards of the Ontario Teachers' Pension Plan, TD Asset Management, USA Funds Inc., and Greenwood College School. She is a recipient of the Ontario Volunteer Award and was honoured by the Women's Executive Network in 2004 as one of Canada's Most Powerful Women: Top 100 in the Trailblazer category.

John Reid is the Audit Leader for KPMG in the Greater Toronto area. During his 35-year career, he has assisted both private and public sector organizations through various stages of strategic planning, business acquisitions, development, and growth management. His experience spans all business sectors and industries with a focus on mergers and acquisitions, technology, and health care. Mr. Reid has served on many hospital boards throughout Canada and has also been a director on many university and college boards.

Appendix F: Scientific Advisory Committee

Perimeter Institute's Scientific Advisory Committee (SAC) provides key support in achieving the Institute's strategic objectives, particularly in the area of recruitment.

Renate Loll, Radboud University (2010-Present), Chair
Professor Loll is a Professor of Theoretical Physics at the Institute for Mathematics, Astrophysics and Particle Physics of the Radboud University in Nijmegen, Netherlands. Her research centres on quantum gravity, the search for a consistent theory that describes the microscopic constituents of spacetime geometry and the quantum-dynamical laws governing their interaction. She has made major contributions to loop quantum gravity and, with her collaborators, has proposed a novel theory of quantum gravity via 'Causal Dynamical Triangulations.' Professor Loll heads one of the largest research groups on non-perturbative quantum gravity worldwide and is the recipient of a prestigious personal VICI-grant of the Netherlands Organisation for Scientific Research. Professor Loll is also a Perimeter Distinguished Visiting Research Chair.

Matthew Fisher, Kavli Institute for Theoretical Physics/University of California, Santa Barbara (2009-Present)
Professor Fisher is a condensed matter theorist whose research has focused on strongly correlated systems, especially low-dimensional systems, Mott insulators, quantum magnetism, and the quantum Hall effect. He 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, and became a Perimeter Distinguished Visiting Research Chair in 2013. Professor Fisher has over 160 publications.

Brian Greene, Columbia University (2010-Present)
Professor Greene is a Professor of Mathematics and Physics at Columbia University, where he is co-Director of the Institute for Strings, Cosmology, and Astroparticle Physics (ISCAP). Professor Greene has made ground-breaking discoveries in superstring theory, exploring the physical implications and mathematical properties of the extra dimensions the theory posits. His current research centres on string cosmology, seeking to understand the physics of the universe's first moments. Professor Greene is well known for his work on communicating theoretical physics for general audiences, and his books include *The Elegant Universe*, which has sold more than a million copies worldwide; *The Fabric of the Cosmos*, which spent six months on The New York Times Best Seller list; and *The Hidden Reality*, which debuted at number 4 on The New York Times bestseller list. A three-part NOVA special based on *The Elegant Universe* won both the Emmy and Peabody Awards.

Erik Peter Verlinde, Institute for Theoretical Physics/University of Amsterdam (2010-Present)
Professor Verlinde is a Professor of Theoretical Physics at the Institute for Theoretical Physics at the University of Amsterdam. He is world renowned for his many contributions, including Verlinde algebra and the Verlinde formula, which are important in conformal field theory and topological field theory. His

research centres on string theory, gravity, cosmology, and black holes. Professor Verlinde has proposed a holographic theory of gravity which appears to lead naturally to the observed values of dark energy in the universe.

Birgitta Whaley, Berkeley Quantum Information and Computation Center/University of California, Berkeley (2010-Present)
Professor Whaley is a Professor in the Department of Chemistry at the University of California, Berkeley, where she is Director of the Berkeley Quantum Information and Computation Center. Professor Whaley's research centres on understanding and manipulating quantum dynamics of atoms, molecules, and nanomaterials in complex environments to explore fundamental issues in quantum behaviour. She has made major contributions to the analysis and control of decoherence and universality in quantum information processing, as well as to the analysis of physical implementations of quantum computation. Professor Whaley is also known for her theory of molecular solvation in nanoscale superfluid helium systems. Her current research includes theoretical analysis of quantum information and computation, coherent control and simulation of complex quantum systems, macroscopic quantum coherence, and quantum effects in biological systems.

Appendix G: Media Highlights

In 2012/13, Perimeter Institute received major coverage in both national and international media, including *The Globe and Mail*, *National Post*, *Toronto Star*, *The Huffington Post*, *Maclean's*, CTV, CBC, *Nature*, *The Walrus*, *TIME Magazine*, *Reader's Digest*, *Wired UK*, and *The Economist*, among others. Some highlights are included below.

Outlet	Headline	Date	Summary
The Huffington Post, Nature	Universe May Not Be Expanding After All, Cosmologist Says	July 21, 2013	This article discusses cosmologist Christof Wetterich of the University of Heidelberg in Germany proposing a radically different interpretation of events — in which the universe is not expanding at all. Perimeter Faculty member Niayesh Afshordi is quoted in article.
MIT Technology Review, Scientific American Blog	The Bell Labs of Quantum Computing	July 21, 2013	This blog identifies Mike Lazaridis as the inventor of the BlackBerry and founder of Perimeter Institute, who now wants to create an industry around quantum computing.
Phys.Org, 100% Solutions	Physicists show self-correcting quantum computers are theoretically possible	June 11, 2013	The article identifies that a team of physicists, including Héctor Bombin of PI, have shown that it's theoretically possible to construct a quantum computer that has the ability to correct itself whenever an error occurs.
The Record	Imagining a quantum future	May 3, 2013	The article discusses the potential technological impacts of quantum physics research.
The Record	The quest for Quantum Valley	April 20, 2013	The article describes "Quantum Valley" and Canada's opportunity in the quantum revolution.
Globe and Mail	New glimpses of ancient light fuel cosmic debate	March 22, 2013	*The Globe*'s science reporter Ivan Semeniuk writes about the Planck mission, quoting Perimeter's Neil Turok.
Globe and Mail	Mike Lazaridis's new quantum leap	March 19, 2013	The article discusses Mike Lazaridis' new venture, Quantum Valley Investments, and the advancements in quantum research taking place in Waterloo Region.
Physics Today	Bookends – Questions and answers with Neil Turok	March 11, 2013	This is an interview with Neil Turok about his new book, *The Universe Within*.
The Walrus	The God Particle	December 2012 Edition	Science freelance writer Dan Falk writes about *The Universe Within* and the relationship between science and religion.
TIME Magazine	A Guidebook to the Universe — and to Ourselves	November 23, 2012	*TIME*'s Michael Lemonick interviews Neil for a book review of *The Universe Within*. Lemonick writes, "… Turok takes you where no physicist has gone before. It's well worth making the journey with him." *(Web-only article)*

Nature	Education: Africa's counting house	November 7, 2012	*Nature* profiles the growth of AIMS across Africa in an extended feature article.
Waterloo Region Record, Metro	Waterloo theorist unlocking secrets of black holes	October 18, 2012	Appearing on the front page of the *Waterloo Region Record*, Linda Givetash provides a high-level overview of the research findings.
National Post	And then there was light	October 18, 2012	Neil Turok discusses the importance of fundamental research in an op-ed.
Maclean's	The secrets of the universe	October 15, 2012	Maclean's published an excerpt from *The Universe Within*.
Globe and Mail	You don't understand quantum physics? Neil Turok will help you	October 12, 2012	Anne McIlroy interviews Neil Turok about *The Universe Within*, discussing the discovery and impact of quantum physics. This appeared in the Saturday paper, Focus section.
Reader's Digest	Getting physical	October 2012 Edition	*Reader's Digest* published a two-page Q&A with Neil Turok.
Toronto Star	Bringing science to the masses	September 29, 2012	*Toronto Star*'s Oakland Ross interviews Neil Turok, and discusses the disconnect between science and society with an optimism for the future.
Phys.Org	For the first time, astronomers have measured the radius of a black hole	September 27, 2012	Phys.Org writes about the research findings.
Waterloo Region Record, Guelph Mercury, Metro	Stephen Hawking's back in Waterloo	September 13, 2012	*The Record*'s Greg Mercer interviews Neil Turok about Hawking's visit, and the research he's working on while he is at Perimeter.
Wired UK Magazine	In Search of Africa's Einstein	August 6, 2012	*Wired UK* profiled Neil and chronicles his role in the founding of AIMS.