2009-10 Annual Report to Industry Canada

Covering the Objectives, Activities and Finances
for the period August 1, 2009 to July 31, 2010 and
Statement of Objectives for Next Year and the Future

Submitted by: Neil Turok, Director
to the Hon. Tony Clement, Minister of Industry
and the Hon. Gary Goodyear, Minister of State (Science and Technology)

Contents

Executive Summary 1

Overview of Perimeter Institute 3

Statement of Objectives for 2009-10 5

Objective 1: Achieve major research breakthroughs 7

Research Highlights 7

Honours, Awards and Major Grants 13

Objective 2: Become the research home of a critical mass of the world's leading theoretical physicists 15

Faculty Recruitment 15

Associate Faculty Recruitment 17

Objective 3: Generate a flow-through of the most promising talent 20

Perimeter Scholars International (PSI) 20

Postdoctoral Researchers 21

Postdoctoral Physicist-in-Residence Program (New Initiative) 22

The GO Program (New Initiative) 22

PhD and Graduate Program 22

Objective 4: Provide a second 'research home' for many of the world's outstanding theorists 24

Stephen Hawking's Inaugural Visit to PI 24

Distinguished Research Chair Appointments 25

Scientific Visitor Program 28

Objective 5: To act as a hub for a network of theoretical physics centres around the world 29

Global Outreach 29

Collaborations and Partnerships 31

Objective 6: Increase PI's role as Canada's focal point for foundational physics research 33

Engagement with Key Experimental Centres 34

The PI Affiliate Program 34

Physics in Canada Special Issue 35

Visits by International Officials and Media 35

Objective 7: Host timely, focused conferences, workshops, seminars and courses 36

Conferences and Workshops 36

Seminars and Colloquia 37
Courses 38
Objective 8: Engage in high impact outreach 39
Programs and Resources for Teachers 40
Student Programs and Products 41
Online Resources 42
Programs for the General Public 44
Objective 9: Create the ultimate environment and infrastructure to support excellence in theoretical physics research 47
Expansion of IT Services and Infrastructure 48
Expanding the Perimeter 49
Overview of Financial Statements, Expenditures, Criteria and Investment Strategy 50
Expenditures by Activity 54
Criteria Applied to Eligible Activities 55
Performance Monitoring – Internal 55
Performance Monitoring – External 55
Investment Strategy 56
Public-Private Partnership 56
Governance 56
Financial − Investment and Management of Funds 57
Objectives for 2010-11 58
Statement of Objectives, 2010-11 58
Appendix A: Perimeter Institute Faculty 59
Faculty 59
Associate Faculty 63
Appendix B: PI Distinguished Research Chairs 67
Appendix C: Perimeter Institute Affiliate Members 71
Appendix D: Perimeter Institute Board of Directors 76
Appendix E: Perimeter Institute Scientific Advisory Committee 78

Executive Summary

2009-10 marked the 10th anniversary of Perimeter Institute for Theoretical Physics (PI), which was founded as an unprecedented public-private investment in foundational theoretical physics, an extremely cost-effective field with an unmatched record of seeding innovations across all of science and technology.

PI's overarching aim is to create and sustain a world-leading centre for foundational theoretical physics research and scientific outreach, promoting research excellence and stimulating major scientific breakthroughs.

The present document reports on progress made during FY 2009-10 (August 1, 2009-July 31, 2010) with respect to the Objectives set out in last year's Annual Report to Industry Canada.

Over the past year, the Institute has made excellent progress under each of the Objectives set out in last year's Annual Report, and met targeted outcomes in each area. These successes 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 goals.

Achievement Highlights, 2009-10:

- ✓ Produced research of the highest calibre, with 271 publications that advanced research at some of the most promising interfaces in theoretical physics;

- ✓ Continued to deepen research expertise across a strategically interconnected set of research areas that is unique worldwide;

- ✓ Built the Institute's research staff toward critical mass by appointing two new Faculty members, three Associate Faculty members, and 14 postdoctoral researchers;

- ✓ Appointed an additional ten of the world's top physicists as Perimeter Institute Distinguished Research Chairs who make Perimeter their second 'research home,' and welcomed PI Distinguished Research Chair Stephen Hawking to Perimeter—and Canada—for the first time;

- ✓ Generated a new flow of scientific talent to Canada through Perimeter Scholars International (PSI), an intensive and innovative new Masters level research training course, whose first class comprised 28 top students from 16 countries;

- ✓ Strengthened PI's role as a focal point for foundational physics research in Canada through joint recruitment of Associate Faculty, establishment of the new PSI Masters program, delivery of 10 advanced courses, and joint sponsorship of nine conferences and workshops;

- ✓ Hosted 387 visiting scientists, including 350 short-term scientific visitors, 17 Visiting Researchers and 15 PI Distinguished Research Chairs;

- ✓ Held 15 timely, focused conferences, workshops and summer schools attended by 691 researchers from around the world, in addition to 242 scientific talks;

- ✓ Launched a new Global Outreach program to share knowledge and expertise in research, training and outreach with emerging centres in math and science internationally, and obtained $20 million in funding from the Government of Canada on behalf of the African Institute For Mathematical Sciences-Next Einstein Initiative (AIMS-NEI);

- ✓ Held a major public science festival, *Quantum to Cosmos: Ideas For the Future*, attended by over 40,000 people on-site plus over one million online and TV viewers; and released a one-hour broadcast documentary, *The Quantum Tamers*, which has won four international awards to date;

- ✓ Delivered high quality programs and products to increasing numbers of secondary school science teachers through EinsteinPlus teachers' camps, and through development of the new PI Teacher Network;

- ✓ Inspired and educated young people on the importance and power of research and innovation by holding the International Summer School for Young Physicists (ISSYP) education camp, giving *Physica Phantastica* and *Power of Ideas* presentations across Canada, and developing new in-class and web-based resources including *The Challenge of Quantum Reality*, "*Meet a Scientist*" interviews, *Virtual ISSYP*, and the new *Alice and Bob in Wonderland* animation series;

- ✓ Executed the first phases of a major facility expansion, *The Stephen Hawking Centre at Perimeter Institute,* on schedule and on budget, and achieved Ontario's first-ever 'Gold Seal' rating for construction quality;

- ✓ Launched a major endowment campaign.

Overview of Perimeter Institute

"...What may be the most ambitious intellectual experiment on Earth."
– New Scientist, November 2008

Theoretical physics is one of the lowest-cost, highest-impact disciplines in science. Just one major discovery in theoretical physics is capable of changing the world, as when Maxwell discovered a unified description of electricity and magnetism, and Marconi applied these ideas to send the first radio signals, or when Einstein's new ideas about light as tiny particles, or 'photons,' eventually led to the laser, medical imaging equipment, CD players, and more.

Today, quantum theory is leading the way toward new materials with extraordinary properties, and computers and communication systems vastly more powerful than today's. Theoretical physics contributes key concepts to fields from astronomy to neuroscience, pure mathematics to computer science. It is above all a creative field, constantly reinventing itself, discovering deeper insights into nature while broadening its range of application.

Perimeter Institute (PI) was founded in 1999 as an independent research institute focused on the greatest challenges facing fundamental theoretical physics in the 21st century, namely, discovering a deeper understanding of the quantum laws of physics and the spacetime arena in which they operate. This mission is built on the twin pillars of 20th century physics: quantum theory, describing the behaviour of matter and energy at atomic and subatomic scales, and general relativity, describing gravity, stars, galaxies and the universe itself. Both theories match a huge range of observations to extraordinary accuracy. However, one of the greatest unsolved problems of modern theoretical physics, and a key objective of PI, is to find a consistent framework which unifies the two theories. This question is central to resolving key puzzles about the physical universe, from understanding the dark energy which shapes its cosmological evolution to determining the essential nature of matter and forces on the smallest subatomic scales. Time and again, history has shown that answering such questions has been transformative.

A complementary part of Perimeter's mission is educational outreach that communicates the importance of basic research, the joys of discovery, and the enduring power of new ideas. Perimeter strives to be a leader in the creation and delivery of innovative programs that engage and inspire students, teachers, and the general public in Canada and beyond.

A Decade of Success

A decade after its creation, Perimeter Institute is a highly respected international centre of basic scientific research, and an innovative and successful Canadian example of a public-private partnership that unites government and philanthropists in a common quest to secure the transformative potential of scientific research.

In its first decade, PI has:

- ✓ Attracted scientists of the highest international calibre to Canada, not only reversing 'brain drain' but also becoming a powerful talent magnet, epitomized by Stephen Hawking's choice of Perimeter—and Canada—as his second 'research home';

- ✓ Catalysed the creation of the Institute for Quantum Computing (IQC), PI's experimental partner institute;

- ✓ Become a renowned training ground for young scientists;

- ✓ Strengthened research quality and productivity across Ontario and nationally through joint appointments and collaborative relationships with Canadian institutions;

- ✓ Become an international nexus of scientific exchange, gathering hundreds of researchers annually from across Canada and around the globe to explore compelling new research directions;

- ✓ Developed award-winning outreach programs providing outstanding educational resources for students and teachers and presenting inspiring events and programs to the general public;

- ✓ Benchmarked all progress under independent peer review and the scrutiny of a Scientific Advisory Committee comprised of pre-eminent international scientists, three of whom are Nobel laureates.

At the end of 2009-10, Perimeter's research staff comprised 12 full-time Faculty members, 12 Associate Faculty jointly appointed with other institutions, and 47 postdoctoral researchers.

Perimeter is now one of the largest and most important centres for training in theoretical physics worldwide: it hosts the largest group of independent postdoctoral researchers in theoretical physics in the world, and with nearly 60 students in its Masters and PhD programs, PI is playing an increasingly important role in building Canada's science and innovation capacity.

As PI looks to the future, the Institute has embarked upon an ambitious strategic plan to fully establish itself as the world's foremost centre for foundational theoretical physics research, training and outreach. In support of this vision, it has commenced an expansion project to create the *Stephen Hawking Centre at Perimeter Institute,* and has launched a major endowment campaign to broaden its base of financial support, in hopes of uniting public and private partners, and the world's best scientific minds, in a shared quest to achieve fundamental breakthroughs that will transform our future.

Statement of Objectives for 2009-10

Objective 1: **Achieve major research breakthroughs** – by continuing to focus on advancing fundamental research, encouraging complementary and multidisciplinary approaches, and instilling a collaborative atmosphere which maximizes cross-fertilization of ideas and increases the probability of breakthroughs.

Objective 2: **Become the research home of a critical mass of the world's leading theoretical physicists** – by continuing top level recruitment initiatives, offering collaboration and interaction opportunities second to none, and fostering cooperative links throughout the Canadian and international research community.

Objective 3: **Generate a flow-through of the most promising talent** – by furthering PI's commitment to recruiting the most promising postdoctoral researchers, facilitating researcher engagement with experimental and observational centres, attracting and training brilliant young graduate students through the PSI program and recruiting the best for further PhD training, and providing research training opportunities to promising undergraduate students.

Objective 4: **Provide a second 'research home' for many of the world's outstanding theorists** – by continuing to recruit top scientists to the Distinguished Research Chairs program, by attracting Visiting Researchers, and through agreements that encourage joint activities between researchers at PI and leading centres throughout the world.

Objective 5: **To act as a hub for a network of theoretical physics centres around the world** – by developing partnerships and collaboration opportunities with centres for theoretical physics in both the developed and the developing world. PI is well placed to assist in the creation of an international network of such centres, in the process branding Canada as a leader in the promotion of fundamental science worldwide.

Objective 6: **Increase PI's role as Canada's focal point for foundational physics research** – by continuing to develop national and international relationships, maximizing technologies allowing remote participation, and fostering research interaction opportunities for Faculty members and Affiliates across the country.

Objective 7: **Host timely, focused conferences, workshops, seminars and courses** – by concentrating on workshops that do not happen anywhere else with top scientists discussing the hottest topics and sharing their research results, as well as through an active seminar program and carefully selected advanced graduate courses for credit at surrounding universities.

Objective 8: **Engage in high impact outreach** – by communicating the importance of basic research and the power of theoretical physics to general audiences, developing brilliant young

Canadians for the field by supporting a network of educators across the country with professional development and resources, and by guiding the very best scientifically-minded students toward a career in theoretical physics. PI will also serve as an international resource for outreach expertise to emerging centres of excellence in the developing world, and will provide resources online and through selective presentations at major international educational gatherings.

Objective 9: **Create the ultimate environment and infrastructure to support excellence in theoretical physics research** – by continuing construction of *The Stephen Hawking Centre at Perimeter Institute*, an expanded facility with the productive research areas and technologies necessary to maximize the possibilities of scientific breakthroughs.

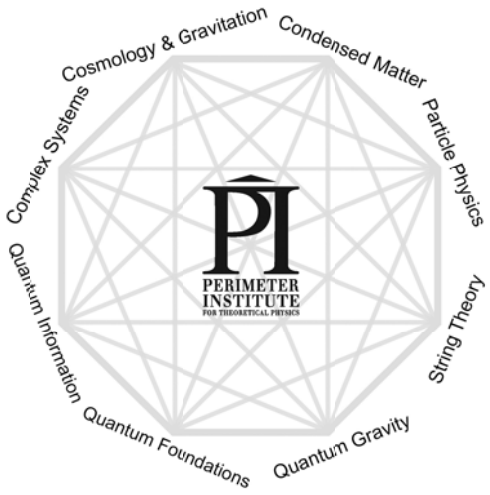
Objective 1: Achieve major research breakthroughs

Summary of Achievements

- Advanced fundamental research through 271 high calibre papers which attracted 533 citations during 2009-10. Since inception, PI researchers have produced 1472 papers appearing in 50 journals, which have attracted 26,430 citations to date[1], attesting to the importance and long-term impact of PI research.

Highlights

Research Highlights



Over the course of the year, PI continued to foster collaborative, interdisciplinary approaches to some of the most challenging problems in the field. The schematic representation above shows PI's research 'space,' which fosters novel insights, or 'sparks,' between strategically interconnected areas. This set of research areas is unique worldwide, and comprises a whole far greater than the sum of its parts, enabling insights gained from each of these fields to promote progress and innovation in all of them.

This long-term strategic vision ensures that Canada plays a leading role in foundational physics research, and the technologies that may arise from it, both now and in the future.

[1] According to Google Scholar and Spires databases, as of July 31, 2010. Each PI publication is counted only once, regardless of how many PI researchers were co-authors.

PI researchers are now leading advances at several of the most active interfaces in fundamental physics. The Institute's unique, multidisciplinary environment was critical to the achievement of a number of important discoveries, several examples of which are outlined below.

"Gauge Theory Loop Operators and Liouville Theory," Jaume Gomis (Perimeter Institute), Takuya Okuda (Perimeter Institute), Nadav Drukker (Humboldt-Universität zu Berlin), Joerg Teschner (Deutsches Elektronen-Synchrotron), [arXiv:0909.1105]

Gauge theory is the underlying theoretical framework describing the four elementary forces in nature. Among these is the strong force, which is described by quantum chromodynamics (QCD). Even though the predictions of QCD have been subjected to intense experimental verification, a key unsolved problem remains: a theoretical description of the 'strong coupling regime,' which is responsible for the experimentally observed and important phenomenon of quark confinement.

In the 1970s, Nobel laureate Gerard 't Hooft introduced a novel type of magnetic gauge theory operators—known as 't Hooft operators—specifically designed to probe quark confinement. In the present work, Faculty member Jaume Gomis, in collaboration with PI postdoctoral researcher Takuya Okuda and international collaborators, proposed the first exact formula for the quantum behaviour of 't Hooft operators in a broad class of four-dimensional supersymmetric gauge theories.

This is the first exact result for this class of important observables in gauge theories, and one of the very few exactly computed quantities in gauge theories. It introduced a novel tool for computing new exact quantities in supersymmetric gauge theories and, by relating 't Hooft operators in gauge theories to defect operators in two-dimensional field theory, provides a theoretical laboratory in which to understand the physical properties of 't Hooft operators. The work has also shed new light on how the strong and weak coupling regimes may be related.

The work, published in the *Journal of High Energy Physics* (JHEP1002, 2010), generated widespread interest internationally, and is a 'TopCite 50+' on the SLAC/SPIRES database. Dr. Gomis was invited to present these results at multiple international conferences, including *Strings 2010*, the premier conference in the area.

"Y-system for Scattering Amplitudes," Luis F. Alday (Institute for Advanced Study (IAS)), Juan Maldacena (IAS), Amit Sever (Perimeter Institute), Pedro Vieira (Perimeter Institute), [arXiv:1002.2459]

In "Y-system for Scattering Amplitudes," PI Faculty member Pedro Vieira and postdoctoral researcher Amit Sever, together with collaborators Luis Alday and Juan Maldacena, both of the IAS in Princeton, computed the minimal area of surfaces which end on a special class of polygons located at the boundary of a space-time of constant negative curvature called Anti-de Sitter space (AdS).

The work represents a major advance for several reasons. It generalized the minimal area problem (also known as the Plateau problem) to a curved space-time. The minimal area problem is an important geometrical problem in a branch of mathematics known as the calculus of variations, which has applications in several fields including engineering. The particular space-time considered plays the central role in the AdS/CFT correspondence, proposed by Dr. Maldacena in 1997, which provides an alternative (dual) description of some particle theories in terms of a theory of quantum gravity (string theory), living in AdS space-time. The results gave the solution to computing polygon Wilson Loops, important non-local objects, at strong coupling in particle theories with AdS duals. For the first time, the work enables gluon scattering amplitudes, the most central observables in particle physics, to be computed at strong coupling, for any number of particles and in any kinematics in particle physics with AdS duals.

This work is the first example of effective use of classical integrability in the computation of scattering amplitudes for generic kinematics, and was presented by Dr. Maldacena at *Strings 2010,* the premier conference in the field. It is hoped that the quantum integrability of these models could be used to compute the full quantum scattering amplitudes and Wilson Loops at any value of the coupling. If achieved, this would amount to the first full solution of a non-trivial particle theory model. Follow-up work is ongoing, and "An Operator Product Expansion for Polygonal null Wilson Loops" (Luis F. Alday, Davide Gaiotto, Juan Maldacena, Amit Sever, Pedro Vieira [arXiv:1006.2788]) represents a step toward this ambitious goal and was presented at *IGST 2010*, the major conference in integrability in gauge/string theories.

The collaboration has also resulted in the development of a productive partnership with the Institute for Advanced Study (see Objective 5). As part of this partnership, the institutes have agreed to hold a series of workshops in "Integrability and Scattering Amplitudes" alternating between Perimeter and the IAS. The first of these took place at the IAS on April 8-9, 2010, while the next will be held at PI on September 15-16, 2010.

Perimeter Institute's scientific environment was instrumental in fostering this research. For example, world-leading expert Juan Maldacena visited PI to do intensive research, which was then written jointly with Davide Gaiotto, who will be joining PI as a faculty member. This work is also closely related to the work of world-leading specialist and PI Faculty member Freddy Cachazo, and PI has the possibility of leading the most exciting developments in this field in the future.

"Perfect Porcupines: Ideal Networks for Low-Frequency Gravitational Wave Astronomy," L. Boyle, submitted to *Physical Review* (2010), [arXIv:1003.4946]

For 400 years, astronomy has been based on the detection of *electromagnetic* radiation; now, physicists believe that detection of *gravitational* radiation will open a new window onto the universe and give birth to a new field: gravitational wave astronomy. It is expected that the first direct detection of gravitational radiation will be achieved during this decade, by the LIGO/VIRGO detectors. Although individual gravitational wave detectors are poor astronomical instruments, it is possible to design

coherent networks of multiple detectors that function together as effective gravitational wave *telescopes*. These networks will play a central role in the future of gravitational wave astronomy.

In this work, Faculty member Latham Boyle introduces and develops an important new concept for such networks that is likely to be important in future designs. A 'porcupine' is a network of gravitational wave detectors in which the individual detectors and the distances between them are short relative to the gravitational wavelengths of interest (such that the arms of the various detectors in the network may be thought of as emanating from nearly the same point in space, like the quills of a frightened porcupine). Gravitational wave frequencies are typically very low (below 30 Hz), corresponding to wavelengths longer than the radius of the Earth; thus, a network of Earth-based detectors would automatically be a porcupine. Dr. Boyle's work focuses on 'perfect porcupines': special network configurations for which the porcupine's sensitivity to an incident gravitational plane wave becomes completely independent of the propagation direction or polarization of the wave. Networks with this property also have a collection of other properties that are desirable from an astronomical standpoint, and are the ideal networks for low frequency gravitational wave astronomy. Having identified this basic design principle, the work proceeds to explicitly present optimal porcupine configurations that can be constructed from a collection of single-arm detectors or a collection of double-arm detectors, like LIGO/VIRGO.

The research atmosphere at PI was crucial to the development of this research, which, by focusing more on basic principles than on particular experiments, has derived results of wide significance to gravitational wave astronomy.

"QIP = PSPACE," Rahul Jain (University of Southern California), Zhengfeng Ji (Perimeter Institute), Sarvagya Upadhyay (Institute of Quantum Computing), John Watrous (Institute of Quantum Computing), *Proceedings of the 42nd ACM Symposium on Theory of Computing (STOC),* 2010, [arXiv:0907.4737]

This result was considered one of the year's most important in quantum information, and indeed in all of theoretical computer science. It was selected for one of eight invited talks at *QIP*, the major annual conference on theoretical quantum computation, and it won the "Best Paper" award at *STOC 2010*, one of the two most prestigious conferences in computer science.

A major topic of interest in the field of quantum information processing over the past few years has been the study of the power of quantum interactive proofs. PSPACE is the complexity class of computations which use space efficiently, but may take a very long time. IP is the class of questions for which an infinitely-powerful (but potentially dishonest) prover can convince a limited-power verifier of the answer through a back-and-forth conversation of reasonable length (an "interactive proof").

A key result of classical computer science states that IP=PSPACE. In other words, the computational power of an interactive conversation is equivalent to the computational power of being able to reuse scratch space many, many times. This means that an interactive proof can in principle be used for many interesting problems, such as proving the best strategy for some deterministic two-player games such as

Go. This result ultimately led to a number of interesting results, including the proof that for certain kinds of optimization problems, even getting a good approximation of the best answer is a computationally difficult task.

In the current work, Dr. Ji and his collaborators extended this result to the context of quantum information, and showed that QIP=PSPACE – in other words, that a quantum interactive proof is no more powerful than a classical interactive proof. Thus, even though a quantum computer can solve some problems much faster than a classical computer, a back-and-forth 'quantum conversation' cannot convince someone of more than can a classical exchange.

The question had been open for a decade, and answering it helps to clarify the picture of quantum complexity classes and how they relate to classical complexity classes. The proof uses semidefinite programming, a technique which has become useful in the field of quantum information, and helps to develop the technique. The result also relates to recent research on multi-prover quantum interactive proofs and quantum complexity theory.

Beyond its scientific importance, the work is a representative example of the many productive research ties between PI and its experimental partner institute, the Institute for Quantum Computing (IQC) at the University of Waterloo. Dr. Ji was a postdoctoral fellow at PI while the work was carried out; Professor Watrous is a PI Affiliate member and Faculty member at IQC; Dr. Jain is a former IQC postdoctoral fellow; and Mr. Upadhyay is an IQC graduate student.

"Ruling Out Multi-Order Interference in Quantum Mechanics," Urbasi Sinha (Institute for Quantum Computing), Christophe Couteau (Institute for Quantum Computing), Thomas Jennewein (Institute for Quantum Computing), Raymond Laflamme (Institute for Quantum Computing and Perimeter Institute), Gregor Weihs (University of Innsbruck), *Science*, 23 July 2010: Vol. 329. no. 5990, pp. 418 – 421. DOI: 10.1126/science.1190545

In this work, researchers from the Institute for Quantum Computing (IQC), Perimeter Institute (PI), and the University of Innsbruck report the results of the most rigorous experimental test to date of Born's rule, one of the central postulates of quantum mechanics.

The researchers developed a variation on the famous 'double slit' experiment, in which a beam of subatomic particles such as photons or electrons is fired at two closely-spaced slits toward a screen. Over many firings, a characteristic wave interference pattern builds up, although the individual particles are sent serially – a puzzling 'wave-particle duality' nonetheless predicted by quantum mechanics.

Born's rule is an axiom of quantum mechanics that defines the probability that a measurement on a quantum system will yield a certain result. In this case, it says that the intensity of the wave pattern is calculated by squaring the sum of the waves that travel through each of two slits. This squaring rule implies that quantum interference is limited to pairs of paths (or pairs of mutually exclusive spacetime alternatives more generally) and conversely if interference is found to be restricted to pairs of alternatives then a version of Born's rule must hold.

The work was motivated by PI researcher Rafael Sorkin's earlier postulate that a generalized version of quantum mechanics might allow multipath (i.e., higher-order) interference. If this were to be found, Born's rule would not suffice to calculate interference patterns correctly, and it would imply the need for a major revision of quantum theory.

The experiment sent individual photons through three slits to see if what was observed matched the predictions of quantum theory. Photons were sent through the three possible two-slit configurations, the measurements were repeated with one slit open at a time, and with all three slits open (and with all three closed to establish a baseline). In this situation, a simple and very general equation expresses the essence of Born's rule: the sum of the 3-slit, 2-slit, 1-slit and 0-slit interference patterns, taken with alternating signs, must vanish. The experimental results confirmed this to within 1%. The results affirm the predictions of quantum mechanics, while opening up new avenues for probing quantum mechanics at still higher degrees of precision. This work is of fundamental significance as part of the ongoing quest for a unified theory of quantum mechanics and gravity, one of the central goals of theoretical physics.

"A quantum Bose-Hubbard model with evolving graph as toy model for emergent spacetime," Alioscia Hamma (Perimeter Institute), Fotini Markopoulou (Perimeter Institute), Seth Lloyd (MIT), Francesco Caravelli (Perimeter Institute), Simone Severini (Institute for Quantum Computing), Klas Markstrom (Umeå universitet), *Phys. Rev. D* 81, 104032 (2010) [DOI 10.1103/PhysRevD.81.104032; arXiv:0911.5075]

This paper, authored by PI postdoctoral fellow Alioscia Hamma, PI Faculty member Fotini Markopoulou and colleagues, is concerned with the point of view that quantum gravity is an emergent, rather than fundamental, phenomenon. In recent years, insights from condensed matter have shown that novel quantum phases of matter can feature all kinds of emergent particles and even emergent gauge symmetries. This paper presents a model of hopping bosons on a lattice that is itself a collection of quantum degrees of freedom, showing that locality and geometry can emerge as the collective behaviour of a simple quantum many-body system.

This work shows how spatial degrees of freedom and matter can be entangled, and implications about the black hole information paradox are studied, namely that entanglement survives even after the black hole has completely evaporated. From the condensed matter point of view, this model is a Hubbard model on a quantum mechanically evolving graph.

The work may open the way to understanding quantum gravity as a quantum phase of matter, and to performing experiments on black hole dynamics in a slab of material. The Perimeter Institute provided the ideal environment for the collaboration of researchers from the Institute itself and other institutions, including MIT, the University College of London, and the Umeå University in Sweden, while the numerical work involved was made possible through PI's access to high performance computing resources (namely SHARCNET).

Honours, Awards and Major Grants

Many PI researchers received national and international recognition for their work in 2009-10. Notable among these were the following:

- Associate Faculty member Cliff Burgess was awarded the 2010 Canadian Association of Physics-Centre de recherches mathématiques (CAP-CRM) Prize in Theoretical and Mathematical Physics, the highest honour in theoretical physics in Canada, for his "broad and deep contributions to theoretical physics";

- PI researcher Christopher Fuchs won the International Quantum Communication Award from the International Conference on Quantum Communication, Measurement and Computation (QCMC) for his "outstanding contributions to the theory of quantum communication including quantum state disturbance";

- Postdoctoral researcher Zhengfeng Ji and collaborators won the "Best Paper Award" at *STOC 2010* for having solved a major open problem in quantum computational complexity;

- Postdoctoral researcher Giulio Chiribella was awarded the 2010 Hermann Weyl Prize from the International Colloquium for Group-Theoretical Methods in Physics;

- Associate Faculty member Michele Mosca was named a Canadian Institute for Advanced Research (CIFAR) Fellow in the Quantum Information program, and one of Waterloo Region's 'Top 40 Under 40';

- PI Director Neil Turok was named a Canadian Institute for Advanced Research (CIFAR) Fellow in the Cosmology and Gravitation program;

- Faculty member Jaume Gomis was given a $150,000 Early Researcher Award from the Ontario Ministry of Research and Innovation;

- Associate Faculty member Niayesh Afshordi was awarded a Discovery Accelerator Supplement (DAS) from the Natural Sciences and Engineering Research Council of Canada (NSERC), one of only eight Accelerator awards given across Canada in physics in 2010;

- Faculty member Fotini Markopoulou was awarded an Alexander von Humboldt Foundation Fellowship (to be held at the Albert Einstein Institute);

- An NSERC Collaborative Research and Development (CRD) grant of $750,000 over three years was awarded to Associate Faculty member Michele Mosca and partners in Waterloo, Calgary, and Montreal to support research on fundamental and applied quantum key distribution networks;

- A US Army Research Office (ARO) grant of US$600,000 over three years was awarded to Associate Faculty member Richard Cleve and partners including Associate Faculty members Michele Mosca and Ashwin Nayak for “Development of Quantum Computing Algorithms”;

- Parampreet Singh was awarded the 2010 S. Chandrasekhar Award of the International Society on General Relativity in Gravitation;

- “The Return of the Phoenix Universe” by Director Neil Turok *et al* received an Honourable Mention at the 2009 Gravity Research Foundation essay competition;

- Postdoctoral researcher Federico Piazza’s paper “The IR-completion of gravity: what happens at Hubble scales?” was named among the “Best of 2009” by the *New Journal of Physics*;

- “Quark Soup al dente: Applied Superstring Theory” by Robert Myers and S.E. Vasquez and “Are loop quantum cosmos never singular?” by postdoctoral researcher Parampreet Singh were selected among the “Highlights of 2008-2009” by the editorial board of *Classical and Quantum Gravity* (CQG).

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

Summary of Achievements

- Appointed two new Faculty members – Latham Boyle and Pedro Vieira – bringing the total number of full-time Faculty members to 12 at the end of 2009-10;

- Appointed three new Associate Faculty members – Niayesh Afshordi (jointly appointed with the University of Waterloo), Luis Lehner (jointly appointed with the University of Guelph), and Canada Excellence Research Chair David Cory (jointly appointed with the University of Waterloo) – bringing the total number of Associate Faculty members to 12 at the end of 2009-10;

- Recruited three junior Faculty members: Natalia Toro (to begin in fall 2010), Philip Schuster (to begin in fall 2010), and Davide Gaiotto (to begin in 2011);

- Recruited four leading scientists to join PI's Scientific Advisory Committee (SAC).

Highlights

PI enjoyed extraordinary success in recruitment over the last year, and continued to build its faculty to critical mass with Faculty and Associate Faculty members of the highest international calibre. The Institute has become an extremely attractive destination for theoretical physicists, and is now able to compete with top institutions worldwide, as demonstrated by several recruitment successes.

During 2009-10, two new Faculty and three Associate Faculty members joined PI; an additional three Faculty have been recruited and will arrive in the coming year. At the end of 2009-10, PI's faculty comprised 12 Faculty and 12 Associate Faculty members (see Appendix A, PI Faculty).

Faculty Recruitment

Latham Boyle joined PI as a junior Faculty member in 2010. He received his PhD in physics in 2006 from Princeton University, under the direction of Paul Steinhardt. From 2006-2009, Dr. Boyle held a Canadian Institute for Theoretical Astrophysics (CITA) Postdoctoral Fellowship; he is also a Junior Fellow of the Canadian Institute for Advanced Research (CIFAR). Dr. Boyle has studied what gravitational wave measurements can teach us about the beginning of the universe; with Paul Steinhardt, he derived a series of '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.

Pedro Vieira joined PI in October 2009 from the Max Planck Institute for Gravitational Physics (Albert Einstein Institute) in Potsdam, Germany, where he was a Junior Scientist from 2008-2009. Dr. Vieira completed his PhD at the École Normale Supérieure Paris and the Centro de Fisica do Porto, Universidade do Porto, under the supervision of Vladimir Kazakov and Miguel Sousa Costa. Dr. Vieira's research concerns the development of new mathematical techniques for gauge and string theories, ultimately aiming toward the solution of a realistic four-dimensional gauge theory. With collaborators, he has recently made important advances which may yield new insights into both gauge theories and quantum gravity, and for calculating scattering amplitudes in particle physics.

New Faculty Recruited for 2010-11:

Natalia Toro will join PI in fall 2010 as a junior Faculty member. She completed her PhD at Harvard in 2007 under the supervision of Nima Arkani-Hamed, a Distinguished Research Chair at Perimeter Institute, and subsequently completed a postdoctoral fellowship at Stanford University SITP. Dr. Toro 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 (CMS) 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 that will search for such forces at the GeV-scale with unrivalled sensitivity at the Thomas Jefferson National Accelerator Facility in Virginia.

Philip Schuster will join PI in fall 2010 as a junior Faculty member. Dr. Schuster completed his PhD in 2007 at Harvard University under the supervision of Nima Arkani-Hamed, and was a Research Associate at SLAC National Accelerator Laboratory from 2007-2010. Dr. 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 a variety of theories that may be discovered at new experiments at the LHC. In collaboration with experimentalists at the LHC, he developed a set of methods to characterize potential new physics signals in a physically transparent manner that makes it easier to identify the underlying theory explaining these signals. He is also a co-spokesperson for the APEX collaboration.

Drs. Schuster and Toro, who are close collaborators, are considered two of the brightest talents in particle physics in the world. Although they are theorists, they have built close links to experimentalists at several leading centres. Techniques they developed have been integrated into the CMS experiment at the LHC, an extraordinary achievement. Several leading institutions competed to hire them, and their successful recruitment at PI not only gives strong evidence of PI's desirability as a top research destination, but also positions the Institute to play a major role at the centre of efforts at the LHC, the largest experiment in human history.

Davide Gaiotto will join PI in 2011 as a junior Faculty member. Dr. Gaiotto received his PhD from Princeton University in 2004 under the supervision of Leonardo Rastelli, was a postdoctoral fellow at Harvard from 2004-2007, and has been a long-term Member at the Institute for Advanced Study since

2007. Dr. Gaiotto works at the interface of quantum field theory and string theory, and has already achieved several important advances. In 2009, he presented a new way of constructing and studying supersymmetric gauge theories which has led to novel techniques for probing the quantum dynamics of gauge theories. Widely considered to be one of the most talented young theorists in his field worldwide, Dr. Gaiotto was recruited to PI over multiple competing offers, including Stanford. His recruitment positions PI to become a leading centre in the increasingly important area of 'high powered' quantum field theory.

Associate Faculty Recruitment

The Associate Faculty program was designed to recruit world-class researchers to Canada and Perimeter through part-time appointments, and it has continued to be very successful in doing so. It has increased the diversity and quality of PI research while strengthening the faculties of our partner universities in Canada. In 2009-10, PI conducted international searches and successfully co-hired three Associate Faculty members in targeted areas. The Institute continues to work with academic partners to recruit exceptional candidates, and to this end recently launched joint recruitment campaigns with the University of Waterloo in the area of cosmology, and with McMaster University in the area of particle physics. Early discussions were also initiated with the University of Guelph for the creation of a chair in computational science (i.e., supercomputing) and with the University of Toronto and the University of British Columbia on the creation of joint positions.

Niayesh Afshordi joined PI's faculty in September 2009 as an Associate Faculty member jointly appointed with the University of Waterloo. Dr. Afshordi completed his PhD at Princeton under the supervision of David Spergel in 2004. He was the Institute for Theory and Computation Fellow at the Harvard-Smithsonian Center for Astrophysics from 2004-2007, and a Distinguished Research Fellow at Perimeter Institute from 2008-2009. Professor Afshordi specializes in interdisciplinary problems in fundamental physics, astrophysics, and cosmology, with particular focus on observational findings that can help address problems in fundamental physics, including the cosmological constant problem. In 2010, Professor Afshordi was awarded a Discovery Accelerator Supplement from the Natural Sciences and Engineering Research Council of Canada (NSERC), one of only eight awarded across Canada in physics.

David Cory joined PI as an Associate Faculty member in June 2010. He is jointly appointed with the Institute for Quantum Computing and the Department of Chemistry at the University of Waterloo, where he holds the Canada Excellence Research Chair in Quantum Information Processing. Professor Cory received his PhD in physical chemistry from Case Western Reserve University in Cleveland, Ohio. He held postdoctoral fellowships at the University of Nijmegen, The Netherlands, and at the National Research Council at the Naval Research Laboratory in Washington, D.C. As a senior scientist at Bruker Instruments, he led research and development activities in nuclear magnetic resonance. In 1992, he joined the Department of Nuclear Science and Engineering at MIT. Since 1996, Professor 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. Professor Cory chairs the advisory committee for CIFAR's Quantum Information Processing program.

Luis Lehner arrived in September 2009 as an Associate Faculty member jointly appointed with the University of Guelph. Dr. Lehner is a pioneer of modern efforts to extract definite predictions for the behaviour of black holes and other strongly gravitating systems from Einstein's equations. With observational tests using gravitational wave astronomy expected in the near future, Dr. Lehner's recruitment positions Perimeter to become a leading centre in this field. Professor Lehner received his PhD from the University of Pittsburgh in 1998 under the direction of Jeffrey Winicour. He held postdoctoral fellowships at the University of Texas at Austin (1998-2000) and the University of British Columbia (2000-2002), and was an Assistant Professor of Physics at Louisiana State University from 2002-2006, before becoming an Associate Professor there from 2006-2009. He is currently an Adjunct Professor at LSU. Professor Lehner received the Honor Prize in 1993 from the National University of Cordoba, Argentina; held a Mellon pre-doctoral fellowship in 1997; won the CGS/UMI outstanding dissertation award and the Nicholas Metropolis award in 1999; and was a PIMS fellow from 2000-2002 and a CITA National Fellow in 2001-2002. He was an Alfred P. Sloan Fellow from 2003-2005 and is currently a CIFAR associate member, a fellow of the Institute of Physics, an editorial Board member of *Classical and Quantum Gravity* and a member of the NSF-Cyber Infrastructure User Advisory Committee.

The Scientific Advisory Committee

PI's Scientific Advisory Committee (SAC) provides key support to the achievement of PI's strategic objectives, particularly in the area of recruitment. Comprised of eminent international scientists, including one Nobel laureate, the SAC provides independent advice and scrutiny on hiring and tenuring decisions, on PI's scientific programs, and on how to ensure that PI's activities meet the highest standards of scientific excellence and objectivity (see Appendix E, Scientific Advisory Committee). Besides meeting annually to review PI's scientific, educational and outreach programmes, the SAC is encouraged to act as PI's 'eyes and ears' within the global theoretical physics community throughout the year. By providing a constant stream of informal ideas and suggestions, the SAC helps PI anticipate new developments, and seize opportunities.

In 2009-10, PI recruited four leading international scientists as SAC members (with appointments to begin September 2010). They include:

Brian 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 groundbreaking 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 *Icarus at the Edge of Time, A Children's Tale*. A three-part NOVA special based on *The Elegant Universe* won both the Emmy and Peabody Awards.

Renate Loll is a Professor of Theoretical Physics and a member of the Institute for Theoretical Physics in the Faculty of Physics and Astronomy at Utrecht University. 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. Professor Loll is a Perimeter Institute Distinguished Research Chair, and is also a lecturer in the Perimeter Scholars International program at the Institute.

Erik Verlinde is a Professor of Theoretical Physics at the Institute for Theoretical Physics at the University of Amsterdam. Professor Verlinde is world-renowned for his many contributions, which include Verlinde algebra and the Verlinde formula, which are important in conformal field theory and topological field theory. His research centres on string theory, gravity, black holes and cosmology. He recently proposed a holographic theory of gravity which appears to lead naturally to the observed values of dark energy in the universe.

Birgitta 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 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 aspects of quantum information science, quantum simulation of exotic topological phases and exploration of quantum effects in biological systems.

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

Summary of Achievements

- Successfully ran first year of Perimeter Scholars International (PSI) research training program, graduating an inaugural class of 28 exceptionally talented students from 16 countries, including six women;
- Hired 14 postdoctoral researchers in 2009-10, and recruited nine postdoctoral fellows for 2010-11 from a record 514 applicants – bringing the total number to 47 at the end of 2009-10;
- Trained 19 PhD students and four MSc students (in addition to those in the PSI program);
- Commenced development of a postdoctoral Physicist-in-Residence pilot program to offer training opportunities with high tech companies throughout Waterloo Region and beyond;
- Commenced development of the GO program, to provide postdoctoral researchers with opportunities to interact with researchers at observational and experimental centres within Canada and internationally;
- Provided research training to six undergraduate students.

Highlights

The lifeblood of theoretical physics is brilliant young people. PI successfully met its objective of generating a flow-through of the most promising talent – by furthering its commitment to recruiting the most promising postdoctoral researchers, attracting and training brilliant young graduate students through the PSI program, recruiting the best for further PhD training, and providing research training opportunities to promising undergraduate students.

Perimeter Scholars International (PSI)

PSI is a major strategic initiative designed to attract exceptionally talented university graduates from around the world to Perimeter and bring them to the cutting edge of theoretical physics in an intense 10-month program. Headed by John Berlinsky, an eminent condensed matter physicist from McMaster University, the syllabus provides an intense overview of the full spectrum of theoretical physics, emphasizing quantum phenomena at all scales.

The program is structurally innovative, combining core courses and topical three-week modules taught by PI Faculty and top international lecturers in their areas of expertise. The 35 PSI Lecturers comprised a 'dream team' faculty, and included five PI Distinguished Research Chairs (Nima Arkani-Hamed, Xiao-Gang Wen, Malcolm Perry, Renate Loll and Leo Kadanoff), all of whom were excited at this new approach to research training. Continuity and ongoing tutorial support was provided by four full-time postdoctoral level Tutors. In the latter part of the program, students completed and defended original research theses, several of which were accepted for publication at competitive international conferences.

The first class comprised 28 students (22 men and six women) selected from a pool of 220 applicants from 16 countries. The calibre of students was extremely high, including, for example, the top graduating student in Physics at Edinburgh University and the top student in Math and Physics at the École Normale Supérieure, Paris. Of the six Canadian students in the program, four held very competitive NSERC scholarships. The first class graduated in June 2010, and the convocation, held in July 2010, included the participation of Professor Stephen Hawking, who is also a PSI Patron.

PSI's first year has been a resounding success. It has fulfilled its major strategic objective, which was to bring talented graduates with great potential to PI and Canada, and to recruit the very best from among them for continued training at PI and surrounding Canadian universities. Six of the 28 graduates are continuing their doctoral training with PI researchers, as well as with researchers at the University of Waterloo, a number which is expected to increase as PSI scales towards a target enrollment of 50 students per year. The majority of the rest are now doing PhDs at top Canadian and international universities including Harvard, Stanford, Imperial College, and McMaster, while some have gone on to industry positions in Canada and abroad at companies including Google and Amazon.

PSI has also served other important objectives: it has strengthened PI's collaborative ties to our close regional partner, the University of Waterloo, which awards a Masters degree to graduates upon completion of the program.

For 2010-11, 31 top students from 15 countries, including 14 women, have been selected. Notably, a large majority of the international Lecturers from last year will be returning, including four Distinguished Research Chairs, attesting to the inherent quality and interest of the program and its students.

Postdoctoral Researchers

Postdoctoral fellows comprise the largest single category of PI's research staff, and indeed PI hosts the largest group of independent postdoctoral researchers in theoretical physics in the world. These motivated and ambitious researchers are critical to the youthful spirit and vibrant research atmosphere at PI. Over the last year, PI continued to prioritize recruitment of independent-minded researchers, and to encourage them to undertake risky, unorthodox, but potentially high-payoff research.

Fourteen postdoctoral researchers joined PI in 2009-10. For 2010-11, numbers were intentionally reduced slightly, to select only the very top tier of applicants, and nine will be incoming for 2010-11. Notably, these nine researchers were selected from a field of 514 applicants, the largest in PI's history, attesting to the Institute's selectiveness, as well as its attractiveness to top-tier talent worldwide.

International recognition of the quality of PI's training continues to grow, and is demonstrated by the fact that despite an extraordinarily competitive market for academic positions, seven departing PI postdoctoral fellows were offered faculty positions within the last year at institutions in Canada and around the world. Notably, two of these chose to accept PI's offer of promotion to Distinguished Postdoctoral Researcher positions over long-term positions at other institutions. (Distinguished Postdoctoral positions offer five-year contracts, while Postdoctoral Researchers are appointed for three years.)

Postdoctoral Physicist-in-Residence Program (New Initiative)

PI commenced early discussions for the development of a pilot program offering postdoctoral researchers residency training opportunities with high tech companies to provide exposure to opportunities outside of academia, maximizing the chance of Canada developing and retaining highly qualified personnel in a broad range of high priority sectors.

The GO Program (New Initiative)

PI recognizes the value in equipping its trainees with knowledge and experience rooted in both theory and experiment. As such, initial discussions were held to create the 'GO Program,' a new initiative that seeks to provide postdoctoral researchers with opportunities to interact with researchers at observational and experimental centres such as the Large Hadron Collider; IQC; SNOLAB; the Planck satellite; VISTA, VLT, the SKA and other giant observatories; and LIGO, LISA and other gravitational wave detectors. These huge, costly experiments are driven by theory, and theory is essential to the analysis and interpretation of the vast data sets they produce. By connecting itself to these efforts, PI can play an instrumental role in shaping the 'big science' projects of the future.

PhD and Graduate Program

Going forward, the PhD program at PI will be administered in tandem with its PSI program, since the PSI program is expected to supply increasing numbers of top students for doctoral study with PI researchers. Admission procedures have been streamlined to ease administration while ensuring the highest standards of excellence among students accepted for doctoral studies with PI researchers and at partner universities. In 2009-10, four doctoral students supervised by PI Faculty and Associate Faculty

graduated, and an additional five were accepted into the program, bringing the total to 25 PhD students in residence at the end of 2009-10, plus four MSc Students (not in the PSI program). Notably, several departing PhD students won competitive postdoctoral fellowships at institutions abroad. As PSI scales to full capacity, it is expected that the PhD program will also grow, with excellence of candidates being the primary factor in program size.

Objective 4: Provide a second 'research home' for many of the world's outstanding theorists

Summary of Achievements

- Appointed ten new PI Distinguished Research Chairs (DRCs);
- Hosted DRC Stephen Hawking for his inaugural visit to Perimeter Institute;
- Hosted 387 visiting scientists, including 350 short-term scientific visitors, 17 Visiting Researchers and 15 PI Distinguished Research Chairs.

Highlights

Stephen Hawking's Inaugural Visit to PI

In June and July 2010, the world's most famous living physicist and PI Distinguished Research Chair, Stephen Hawking, made his inaugural visit to PI. He found the environment at PI both exciting and highly conducive to productive research.

Although Professor Hawking's visit focused mainly on his own research, he participated fully in all aspects of life at the Institute. He attended the "Cosmological Frontiers in Fundamental Physics" conference, where his own research was presented by collaborator Thomas Hertog. As Patron of the PSI Masters program, Professor Hawking celebrated with the inaugural graduating class at their convocation. He participated in PI's Outreach program by giving a talk about his life and research which was broadcast to Canadians via TVO and CPAC in English and French (see Objective 8). This was followed by a second, special event with the Prime Minister of Canada (see Objective 5).

The theme of Professor Hawking's talk was "Special places and times," and in it he drew an explicit parallel between PI's exceptional research culture and the remarkably fruitful period at Cambridge which fed his own landmark discoveries, and ended by saying, "I am hoping, and expecting, great things will happen here."

In short, Professor Hawking's visit was extraordinarily successful: he found it productive from a research perspective, it greatly added to the excitement of life at the Institute, and it garnered widespread national and international media attention that raised PI's—and Canada's—profile as a scientific leader.

Distinguished Research Chair Appointments

The PI Distinguished Research Chairs (DRC) Program has proven to be a resounding success that has enriched the life of the Institute in many ways, and showcased Canada as an international leader in science.

The program is unique worldwide and was established in 2008 to bring world-class researchers to PI on a regular basis. While retaining their permanent positions at home, DRCs are appointed for three-year terms and visit PI for extended periods each year to do research, collaborate and in some cases to teach at PSI. They include world-leading figures such as Stephen Hawking and bright young stars such as Patrick Hayden (McGill) and Guifre Vidal (Queensland). They span an enormous range of expertise, including quantum foundations, particle physics, condensed matter, cosmology, quantum gravity, and other branches of physics.

Over the last year, PI successfully appointed 10 new Distinguished Research Chairs, bringing the current total to 20 (see Appendix B, PI Distinguished Research Chairs). The fact that so many top-tier researchers have joined with Perimeter is an outstanding endorsement of its vision and is helping to raise Canada's profile as an international leader in science. In this regard, it is worth noting that two of PI's Distinguished Research Chairs (Yakir Aharonov and Ignacio Cirac) were widely tipped as potential winners of last year's Nobel Prize for physics.

The continuous flow of top scientists enriches PI's research and makes it an even more attractive destination for top research talent. Over the last year, 15 PI DRCs came to do research at PI, including several who made multiple visits. Encouragingly, many DRCs participated in several areas of the Institute's programming—as Public Lecture speakers, as Lecturers in the PSI Masters program, and as scientific organizers of conferences and workshops. DRCs also represent PI at other institutions: DRC Leo Kadanoff, for example, acts as the liaison between PI and the Joseph L. Rotman Institute of Science and Values at the University of Western Ontario.

The new appointments include the following:

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. Dr. Aharonov is on the faculty of Perimeter Scholars International.

Patrick Hayden holds the Canada Research Chair in the Physics of Information at McGill University. His research focuses on finding efficient methods for performing the communication tasks that will be required for large-scale quantum information processing. This includes the development of methods for

reliably sending quantum states through 'noisy' media and for protecting quantum information from unauthorized manipulation. He has also applied these techniques to the question of information loss from black holes. Among Dr. Hayden's honours, he is a past Alfred P. Sloan Foundation Fellow and Rhodes Scholar.

Christopher Isham is a Senior Research Investigator and Emeritus Professor of Theoretical Physics at Imperial College London. He is a former Senior Dean of the College. Dr. Isham has made many important contributions in the fields of quantum gravity and the foundations of quantum mechanics. Motivated by the "problem of time" in quantum gravity, he developed a new approach to quantum theory known as the "HPO formalism" that enables the theory to be extended to situations where there is no normal notion of time (such as in Einstein's theory of general relativity). Since the late 1990s, Dr. Isham has been developing a completely new approach to formulating theories of physics based on the mathematical concept of a "topos." This gives a radically new way of understanding the traditional problems of quantum theory as well as providing a framework in which to develop new theories that would not have been conceived using standard mathematics. From 2001-2005, Dr. Isham was a member of Perimeter Institute's Scientific Advisory Committee; in 2005, he was the Chair of the Committee.

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 National Medal of Science (US), 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. Dr. Kadanoff is on the faculty of Perimeter Scholars International.

Renate Loll is a Professor of Theoretical Physics and a member of the Institute for Theoretical Physics in the Faculty of Physics and Astronomy at Utrecht University. 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. She is also a Faculty member of Perimeter Scholars International.

Malcolm Perry is a Professor of Theoretical Physics in the Department of Applied Mathematics and Theoretical Physics at the University of Cambridge and a Fellow of Trinity College, Cambridge. His research centres upon general relativity, supergravity and string theory. Dr. Perry has made major contributions to string theory, Euclidean quantum gravity, and our understanding of black hole

radiation. With Perimeter Institute Faculty member Robert Myers, he developed the Myers-Perry metric, which shows how to construct black holes in the higher spacetime dimensions associated with string theory. Dr. Perry's honours include an Sc.D. from the University of Cambridge. Dr. Perry is also on the faculty of Perimeter Scholars International.

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).

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.

Guifre Vidal is a Professor in the School of Physical Sciences at the University of Queensland and has made important contributions to the development of quantum information science, with applications to condensed matter theory. His research explores the phenomenon of entanglement, the renormalization group, and the development of tensor network algorithms to simulate quantum systems. Dr. Vidal's past honours include a Marie Curie Fellowship, awarded by the European Union, and a Sherman Fairchild Foundation Fellowship. He is a Federation Fellow of the Australian Research Council.

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 Alfred P. Sloan Foundation 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.

Scientific Visitor Program

PI continued its active scientific visitor program, which enables PI residents and their collaborators to work intensively on research. Over the past year, Perimeter hosted 387 visiting scientists, including 350 short-term scientific visitors, and 15 PI Distinguished Research Chairs. 19 Visiting Researchers (formerly called “Long-Term Visitors”) accepted PI’s invitation to work at Perimeter during leaves of absence from their home universities.

The visitor program has also proved successful as a recruitment tool, giving potential faculty recruits an opportunity to experience the ‘PI advantage’ in maximizing their research productivity. The visitor program has also had wider impact, in terms of bringing world-leading researchers to Waterloo and Canada. Quantum computing pioneer David Cory, for example, was recently appointed as a Canada Excellence Research Chair in Quantum Information at the Institute for Quantum Computing at the University of Waterloo. Dr. Cory was a long-term PI visitor throughout 2009-10, and the prospect of ongoing interactions at PI was an important factor in strengthening the appeal of a move to Waterloo from MIT. Professor Cory recently accepted a joint Associate Faculty appointment with PI.

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

Summary of Achievements

- Established a major Global Outreach initiative and hired Suzanne Corbeil to lead it;
- Submitted a 'Smart Aid' proposal to the Government of Canada on behalf of the African Institute for Mathematical Sciences-Next Einstein Initiative (AIMS-NEI). The Government announced $20 million in funding to expand this "revolutionary approach to international development" into a pan-African network that will build Africa's science and technology capacity;
- Initiated new partnerships with the Center for Theoretical Science at Princeton, the Institute for Advanced Study at Princeton, the Abdus Salam International Centre for Theoretical Physics (ICTP), and the Centro de Fisica do Porto (CFP);
- Partnered on four joint workshops with surrounding universities, and sponsored or partnered in five off-site conferences and symposia.

Highlights

Global Outreach

In 2009, PI launched its Global Outreach program to further its objective of serving as a resource and stimulus for theoretical physics globally. The mandate of the program is to share PI's expertise (not funding, which others provide), to assist the emergence of innovative, excellent centres of teaching and research in high level math and physics across the developing world.

Over the past year, Suzanne Corbeil was hired to lead PI's new Global Outreach initiative. Ms. Corbeil is a former Vice-President of External Relations and Communications at the Canada Foundation for Innovation (CFI) with strong ties to the Canadian Science and Technology policy community. She is also the Founding Chair of the Science Media Centre of Canada.

Many PI researchers and staff are strongly motivated to contribute to scientific training initiatives internationally. Faculty member Pedro Vieira spearheaded the development of a collaboration with the Centro do Fisica do Porto in Portugal (see below), and Associate Faculty member Luis Lehner began developing a proposal for a research training centre in Latin America. In a similar vein, there are clear

opportunities for PI's education outreach to work with centres in other countries to develop regionally-appropriate scientific outreach programs of their own.

Through Global Outreach, PI can contribute meaningfully to international development and ultimately help to build science and technology capacity within developing nations. In a globalizing world, this will in turn help PI, and Canada, by increasing the pool of talent that the field draws upon, and bringing some of this talent to PI and to Canada. It is expected that Global Outreach will be an exciting area of PI efforts going forward that will enhance all aspects of the Institute's activities. Over the long term, it may yield significant benefits to developing countries, and to Canada, through attraction of talent, and by showing Canada to be a leading knowledge nation.

'Smart Aid' Proposal for AIMS-NEI

PI Global Outreach adopted the African Institute for Mathematical Sciences-Next Einstein Initiative (AIMS-NEI, www.nexteinstein.org) as the first focus of its activities. Founded by PI's Director Neil Turok in 2003, AIMS is a pan-African centre of excellence delivering advanced mathematical and scientific education to exceptional African graduates. Outstanding lecturers from around the world train AIMS students to become independent thinkers and problem solvers with the advanced skills needed for a range of priority sectors in Africa.

In fall 2009, PI submitted a 'Smart Aid' proposal to the Canadian government to expand AIMS into a pan-African network of centres that will rapidly and dramatically increase science and technology capacity in Africa by developing the talent of its brightest young minds.

PI proposed to coordinate the involvement of academic partners in both developed and developing countries, and to share its knowledge and expertise with the appropriate Canadian international aid agencies, such as CIDA, IDRC and others, to ensure a sound, high impact investment and provide a high visibility opportunity for Canada.

On July 6, 2010, Prime Minister Stephen Harper came to PI to announce new federal funding of $20 million to support the establishment of a network of five AIMS centres across Africa, calling it a "revolutionary approach to international development."

While the 'Smart Aid' proposal to the Canadian government was undoubtedly the highlight of the year, PI Global Outreach also put forward a $2 million funding proposal to Google (decision pending), launched a quarterly AIMS-NEI newsletter, and initiated the 'One for Many' project, which seeks to identify academic partners who wish to sponsor AIMS students and to establish a two-way flow of academics and students between their institutions and AIMS centres.

Collaborations and Partnerships

PI continued to strengthen existing partnerships within Canada and internationally. Several of these, such as PI's partnership with the Canadian Institute for Theoretical Astrophysics (CITA), the Laboratoire Astroparticule et Cosmologie (APC) and the Solvay Institute (Brussels), have been ongoing for several years, and have helped to form robust linkages between PI and other institutions.

Highlights included:

- "New Perspectives on the Quantum State" (September 27-October 10, 2009), held as part of the Perimeter Institute-Australia Foundations (PIAF) partnership in quantum foundations;
- "Random Matrix Techniques in Quantum Information Theory" (July 4-6, 2010), held in partnership with the Fields Institute at the University of Toronto;
- "Cosmological Frontiers in Fundamental Physics" (June 15-18, 2010), the fourth workshop in an ongoing series, held in partnership with the Laboratoire Astroparticule et Cosmologie (APC) and the Solvay Institute (Brussels) (see Objective 7);
- The continuation of successful "PI-CITA Days" held in conjunction with the Canadian Institute for Theoretical Astrophysics (CITA) and the Canadian Centre for Advanced Research (CIFAR).

In addition, PI co-sponsored five off-site conferences, workshops, and symposia, including:

- "Workshop on Theory of Quantum Computation, Communication and Cryptography" (held at the University of Waterloo)
- "Emergent Gravity IV" conference (held at UBC)
- "Lake Louise Winter Institute" (held at University of Alberta)
- "Strong and Electroweak Matter 2010" (held at McGill)
- "Mathematica Summer School" (held at Universidade do Porto)

New Partnerships

Abdus Salam International Centre for Theoretical Physics (ICTP): Fernando Quevedo, the recently appointed Director of the Abdus Salam International Centre for Theoretical Physics (ICTP) in Trieste, visited PI for a month in the fall of 2009. His visit to PI laid the groundwork for early discussions about potential collaborations on several fronts to promote theoretical physics globally. One potential area of collaboration is assisting centres in the developing world to develop IT capacity efficiently and cost-effectively, an area of ICTP strength. Since his visit to PI, Professor Quevedo has joined the Board of AIMS-NEI and has pledged ICTP as the European partner for AIMS-NEI.

The Institute for Advanced Study (IAS): Ongoing work between researchers at PI and the Institute for Advanced Study (IAS) in Princeton has deepened collaboration between the institutes and led to a new series of workshops on problems relating to N=4 supersymmetric gauge theory. Workshops take place every six months and alternate venues between PI and IAS. The first of these took place at the IAS on

April 8-9, 2010, while the next will be held at PI on September 15-16, 2010. In addition, a mini-course, "New Developments in N=2 Supersymmetric Gauge Theories," took place in February 2010, and was led by Davide Gaiotto, of the Institute for Advanced Study (who was recently recruited as a PI junior Faculty member, to arrive in 2011).

University of Toronto/ATLAS: This new partnership aims to facilitate PI researchers' engagement with phenomenologists and experimentalists in the particle physics community generally, and in particular with the ATLAS experimental collaboration at the University of Toronto, which has ties with ongoing work at the LHC. Two successful joint meetings were held, modeled on the successful "PI-CITA Days" that have been held for several years, and these are expected to continue.

Centro de Fisica do Porto (CFP): In 2009, PI entered into a five-year partnership with the Centro de Fisica do Porto (CFP) which provides for an annual *Mathematica* Summer School in Theoretical Physics (alternating between CFP and PI), funding for up to two PSI students proposed by CFP, and a joint four-year postdoctoral researcher position. Through this partnership, PI plans to host the second edition of the *Mathematica* Summer School at the Institute in the summer of 2011. This innovative and extremely popular workshop is based on the increasing importance of computation in theoretical physics research for both numerical and analytical work. It brings together theoretical physicists at all levels to learn how to use *Mathematica,* a leading scientific software, in various topical research areas. The first school was devoted to integrability and gauge/string dualities, a "hot" area with connections to numerous other areas, such as condensed matter and mathematical physics.

Center for Theoretical Science (CTS) at Princeton: This new collaboration has established a biannual workshop series on problems in inflationary cosmology with the Princeton Center for Theoretical Science, with each institute alternating as the host venue for the workshop.

Objective 6: Increase PI's role as Canada's focal point for foundational physics research

Summary of Achievements

- Strengthened physics research nationally through joint Associate Faculty recruitment (see Objective 2), and the appointment of 29 new Affiliate members in 2009-10, bringing the total to 95;

- Partnered with the University of Waterloo to deliver the PSI Masters program, and involved faculty from several Canadian universities as PSI Lecturers (see Objective 3);

- Partnered on four joint workshops with surrounding universities and co-sponsored five off-site conferences and symposia with other institutions (see Objective 7);

- Held ten courses for Canadian university students (see Objective 7) and delivered on-site courses remotely via AccessGrid to students at several area universities;

- Prepared a full theme issue of *Physics in Canada* at the request of the Canadian Association of Physicists (CAP);

- Continued to build strong relationships with Canadian physics facilities such as IQC, SNOLAB, TRIUMF, CITA, and CIFAR;

- Welcomed Consuls General, Ambassadors and senior officials, and national and international journalists, showcasing PI's leading international role in basic research, and generating substantial, positive media coverage.

Highlights

PI has become a hub of theoretical physics in Canada. Perhaps the strongest evidence that PI is considered a focal point of research is the fact that in July 2010, Prime Minister Stephen Harper chose PI as the appropriate locale to announce the Banting Postdoctoral Fellowships program, a new initiative which seeks to bring the very brightest early career researchers from around the world to Canada.

In 2009-10, the Institute continued to provide unique resources to the national scientific community through courses, seminars, and workshops (see Objective 7), and attracted top talent to Canada through the PSI program (see Objective 3). The Institute also continued to cultivate partnerships with relevant members of Canada's physics community at many levels, including recruitment (see Objective 2) and

joint organization of workshops and conferences, and by enabling researchers from across Canada to work with PI researchers through Affiliate memberships (see below).

Engagement with Key Experimental Centres

An important element of PI's strategy is to increase its engagement with key experimental centres internationally. In doing so, PI is positioning Canada to play a central role in the largest 'big science' experimental efforts of our time, including those at the Large Hadron Collider (LHC) at CERN, the Planck satellite, and upcoming gravitational wave detectors such as LIGO and LISA. Even a small number of theorists, working in a focused way, can have an enormous impact on these massive international experiments, by pointing out new signals to look for, better ways to analyse and interpret the data, and key physics targets to guide the design of new experiments.

The recent recruitment of Natalia Toro and Philip Schuster provides an example of this highly cost-effective strategy: by recruiting these two leading theorists who are already playing key roles in experiments at the LHC, PI has gained a place at the centre of the largest and most expensive experiment in history (see Objective 3).

A second element of the strategy is PI's planned GO Program (see Objective 3), which will seek to establish a two-way flow of researchers to and from leading experimental and observational centres. Initial discussions to develop this new program took place in 2009-10. In addition, discussions on collaboration opportunities were held with relevant members of the Canadian experimental community, including the SNOLAB particle accelerator facility in Sudbury, the TRIUMF national particle physics laboratory, and the Canadian Light Source synchrotron in Saskatoon. The initiation of an ongoing series of "PI-ATLAS-LHC Days" in fall 2009 represents another promising step in this direction (see Objective 5).

The PI Affiliate Program

In 2009-10, PI added 29 new Affiliate members, bringing the total to 95 Affiliate members drawn from universities across the country. Affiliates are select faculty members at Canadian universities who are invited for regular informal visits to PI for scientific collaboration and the opportunity to be involved in the Institute's research activities. By fostering regional and national research links between PI and Canadian universities, the Affiliate program is helping to strengthen the Canadian physics community as a whole, while broadening the base of research at PI (see Appendix C, PI Affiliates listing).

Physics in Canada Special Issue

The Canadian Association of Physicists (CAP) is Canada's national professional organization for physicists, and the majority of Canadian physicists in industry, university and government laboratories are members of the Association. In 2009, PI was asked to author a special theme issue of their quarterly journal, *Physics in Canada.* The resulting publication, "A Peek Inside the Perimeter Institute" (April-June 2010), included 18 articles (plus one in French) and gave an extensive survey of PI's research, training, and outreach activities. The issue has received enthusiastic praise and has been distributed well beyond the usual subscriber base of 1800, to public and private funders, to physics educators, and to selected media and science communicators. The full issue is also available free via both the PI and CAP websites.

Visits by International Officials and Media

The rapid growth and success of Perimeter's research, training and outreach activities have garnered international attention, showcasing Canada as a hotbed of high-quality, cutting-edge research and as a magnet for top talent. In 2009-10, representatives from the United States, China and Germany visited PI to learn about its activities, operations and vision as well as the novel public-private partnership it is grounded upon.

PI attracted an increasing amount of widespread and positive national and international media coverage of its science and outreach activities. PI welcomed many senior national and international journalists on-site from top media outlets such as *The Globe and Mail*, *Les Échos*, *Maclean's*, *The Wall Street Journal*, *Le Figaro*, CBC Radio and Television, and ABC's *The Science Show*, among others. Of particular note were the following:

- BBC's long-running science documentary program *Horizon* came to PI in June 2010 to film a program titled "What Happened Before the Big Bang?" and interviewed PI Director Neil Turok, Faculty member Lee Smolin, postdoctoral fellow Parampreet Singh, and PI Distinguished Research Chair Leonard Susskind;
- Paul Wells, Senior Columnist for *Maclean's* magazine, visited PI for a four-week stay in June-July 2010 as part of his research for a feature article on the Institute to appear in a special "Re-Think" edition on innovation;
- Jennifer Barone, News Editor for *DISCOVER* Magazine, visited Perimeter Institute in June 2010, and will include interview material from the visit in the magazine's 30th Anniversary Special Issue to be released in fall 2010.

Objective 7: Host timely, focused conferences, workshops, seminars and courses

Summary of Achievements

- Held 15 timely, focused conferences and workshops, attended by 691 scientists from around the world;
- Presented 242 scientific talks (208 seminars, 34 colloquia);
- Partnered on four joint workshops with surrounding universities (see Objective 5);
- Gave ten courses to researchers and students from surrounding universities (five credit and five non-credit);
- Continued to develop PIRSA (Perimeter Institute Recorded Seminar Archive) as a leading international archival resource.

Highlights

Conferences and Workshops

The Institute held 15 conferences in 2009-10 and continued to act as a major global node of exchange for cutting-edge research in theoretical physics. The strategy of carefully selecting topics and areas of the greatest interest with strong potential for significant outcomes has proven successful, and several conferences held at PI over the year were the first to be held worldwide on new discoveries and topics.

The following conferences and workshops are worthy of particular note as having been landmarks in several fields:

- **"Gravity at a Lifshitz Point"** (November 8-10, 2009). This was the first gathering to be held worldwide on the implications of Petr Hořava's recent proposal for a modified theory of gravity, which has generated great excitement internationally. The workshop was co-organized by PI postdoctoral researcher Dario Benedetti and Professor Hořava himself. It enabled a clear picture of the status of this theory to emerge among key researchers and has stimulated new ideas and collaborations both within and outside PI. All talks can be viewed online at: http://pirsa.org/C09026.
- **"Emergence and Entanglement"** (May 25-29, 2010). This was widely regarded as a pioneering workshop in a very exciting new research direction of strongly quantum new phases of matter, such as topological insulators and quantum spin liquids, which are likely to be of great

technological importance in the near future. These quantum systems show novel behaviour of the whole system emerging from the collective behaviour and interaction of the constituent local degrees of freedom. It appears that the long-range quantum entanglement in those systems play a critical role in generating those novel phenomena. The workshop brought together, for the first time, theorists in condensed matter, quantum information theory, and string theory to discuss the topics of emergence and entanglement in quantum many-body systems. The program included talks from 30 high profile researchers, including Nobel laureate Sir Anthony Leggett, and is likely to have lasting impact on the development of condensed matter theory in this area. PI was able to host such a high-calibre workshop, even though the Institute presently does not have any faculty in condensed matter, because of the involvement of two PI DRCs, Xiao-Gang Wen (MIT) and Subir Sachdev (Harvard), as scientific organizers. Guifre Vidal, another PI DRC, also participated in the workshop. All talks can be viewed online at: http://pirsa.org/C10012/3.

- **"Cosmological Frontiers in Fundamental Physics"** (June 15-18, 2010). This was the fourth in a series of workshops organized jointly by the International Solvay Institutes, APC (Université Paris VII, Paris) and Perimeter Institute, a highly productive ongoing partnership between PI, Solvay and APC. Recent research conducted by PI DRC Stephen Hawking was presented by his collaborator, Thomas Hertog, with Professor Hawking in attendance. PI DRC Leonard Susskind also participated in this workshop. The event provided a valuable forum for exchange on key developments at the interface of cosmology and fundamental physics. All talks can be viewed online at: http://pirsa.org/C10014.

Seminars and Colloquia

PI held 208 seminars and 34 colloquia in 2009-10. Eight active weekly seminar series continued to foster collaborations in Canada and served to share and disseminate knowledge from leading researchers around the globe. Particularly notable among these were talks by PI DRCs Leonard Susskind, Yakir Aharonov, Juan Maldacena, Ashoke Sen, and Mark Wise.

All talks held at PI can be viewed online on PIRSA, the Perimeter Institute Recorded Seminar Archive at www.pirsa.org, a permanent, free, searchable, and citable archive of video recorded seminars, conferences, workshops, and courses, developed by Perimeter Institute to foster knowledge sharing and deliver current research to the international scientific community. During the reporting period, 45,004 unique visitors from 151 countries accessed PIRSA, an increase of 35% over the same period last year. New and returning users are also accessing PIRSA more frequently, as demonstrated by the 63% increase in the number of visits, representing over 375,363 page views. PIRSA has become a key resource for the international scientific community, as evidenced by the significant rise in traffic to the site.

Courses

PI capitalizes on the expertise of its resident researchers and visiting scientists to substantially enhance the course offerings of surrounding universities. In addition to courses held through the PSI program, the Institute continued to expand its course offerings to residents and students with a mix of focused short courses and longer accredited courses offered in conjunction with surrounding universities. Highlights of the five credit and five non-credit courses given over the last year included James Wells' (CERN) mini-course, "Beyond the Standard Model Physics and the LHC" (March-April 2010), "Foundations and Interpretation of Quantum Theory" (January-April 2010), given by Raymond Laflamme and Joseph Emerson, and "New Developments in N=2 Supersymmetric Gauge Theories" (February 2010), given by Davide Gaiotto of the Institute for Advanced Study (now recruited as a PI junior Faculty member, to arrive in 2011).

Objective 8: Engage in high impact outreach

Summary of Achievements

- Held *Quantum to Cosmos: Ideas for the Future* science festival for over 40,000 on-site and one million online and TV viewers;

- Produced and distributed a one-hour broadcast documentary, *The Quantum Tamers: Revealing Our Weird and Wired Future,* which has won four awards at international film festivals;

- Held EinsteinPlus summer camp at PI for 27 teachers in August 2009, plus 37 in July 2010, and delivered on-location teacher workshops to over 200 teachers across Canada and internationally;

- Scaled up the PI Teacher Network, using a 'Train the Trainer' approach to deliver an additional 51 workshops and share PI resources with 1,011 teachers across Canada and beyond;

- Piloted webinar technology to increase reach and impact of programs for teachers, particularly in remote areas;

- Held the International Summer School for Young Physicists (ISSYP) at PI for 37 Canadian and international students in August 2009, plus 40 participants in July 2010; initiated *Go Physics!,* a travelling one-day camp designed to give a snapshot of ISSYP physics excitement to senior physics students across Canada;

- Engaged over 6,000 high school students across Canada with *Physica Phantastica* on-location presentations, and the 'I Love Science' video contest;

- Produced new in-class and web-based resources, including *The Challenge of Quantum Reality, Everyday Einstein: GPS and Relativity,* and *Alice and Bob in Wonderland*, and supplemented existing online resources, including *Meet A Scientist* and the *Virtual ISSYP;*

- Partnered with other outreach organizations, such the Canada Wide Science Fair, to provide high quality outreach to students in grades 7 through 12 across Canada.

Highlights

Programs and Resources for Teachers

EinsteinPlus National Teachers' Workshop

Teachers from across Canada and around the world attended the Institute's EinsteinPlus National Teachers' Workshop (E+) on modern physics (27 in summer 2009, plus another 37 participants in July 2010). This one-week, intensive, residential workshop for high school educators focuses on how to better convey key concepts in modern physics. Participants were introduced to PI's latest *Explorations* in-class resources, and provided input on future modules in development. This feedback ensures that the resources are grounded in sound pedagogy and will be embraced by the larger educational community. E+ alumni then return home to conduct remote workshops for fellow physics educators in their region.

On-location Teacher Workshops

Perimeter Outreach staff delivered workshops to educators at conferences in Canada and abroad, reaching over 200 influential teachers at the Science Teachers' Association of Ontario conference, British Columbia's Science Teaching Catalyst conference, and the Ontario Association of Physics Teachers conference. The presentations gave high school science teachers pedagogical techniques for teaching aspects of modern physics, served as distribution nodes for *Perimeter Explorations* in-class content, and provided valuable feedback on new PI material in development. A plan is now in place to deliver presentations in every province and territory of Canada on a four-year cycle, in order to ensure a personal connection between PI and educational organizations across the country.

Outreach staff also provided workshops internationally at the annual conference of the Physics Teaching Resource Agents (PTRA), North America's largest physics education group, and again held a "Mini-EinsteinPlus" for 40 top European physics teachers from over 30 countries at the High School Teacher (HST) Workshop at CERN. This involvement, by request, is a strong endorsement for PI's superior outreach tools and techniques and exemplifies Canada's role in science communication to the world.

PI Teacher Network

Over the last year, Outreach staff devoted significant efforts to putting the PI Teacher Network in place. The network employs a 'train the trainer' approach, providing selected teachers drawn from EinsteinPlus and PI's on-location teacher workshops with additional instruction on how to share the Institute's resources. These teachers in turn deliver workshops for other educators in their home districts, scaling up the reach of PI's in-class resources across Canada. Over the last year, PI Teacher Network members gave 51 workshops in eight provinces and territories across Canada, reaching 1,011 more educators, and at least 45,000 more students than PI staff could have served on their own.

Educational Resources

Perimeter Inspirations: A recent CFI/Ipsos Reid study (June 2010) indicates that there is a critical window of opportunity between the ages of 12 and 18 in which to inspire young people about science. *Inspirations* programming is designed with an emphasis on capturing the imagination of junior high school students, our future innovators, inventors and entrepreneurs, with the intention of sparking their interest and motivating them to continue to take math and science in Grades 10 through 12. The first module in the series, *Everyday Einstein: GPS and Relativity,* was released in July of 2010.

Perimeter Explorations: During later grades, *Explorations* modules delve deeper into more challenging ideas and technical content, in order to reinforce students' scientific inclinations and provide excellent preparation for post-secondary education in math, science and engineering.

Perimeter Explorations in-class resources continue to be the very best vehicle to share challenging ideas in modern physics in highly visual and hands-on ways. The kits allow educators to provide PI content to greater numbers of students than Outreach staff can reach on their own. The second module, *The Challenge of Quantum Reality*, consisting of a 30-minute video and teacher guide containing hands-on activities for students, was distributed to over 1,000 teachers and received exceptional levels of endorsement, with 98 percent of 850 educators surveyed declaring they would use the resource with their classes. Distribution of modules – *The Mystery of Dark Matter, The Challenge of Quantum Reality,* and the popular *Planck's Constant LED* activity – surpassed 4,500 kits delivered across Canada and beyond. This translates to reaching 200,000 students annually, which will continue year over year as each module is re-used.

Student Programs and Products

International Summer School for Young Physicists (ISSYP)

Now widely regarded as the best physics camp in the world, ISSYP provides Canadian and international students (aged 16-19) who show strong scientific promise with the opportunity to come to PI for two weeks each year to take part in lessons on modern physics, mentoring sessions with top scientists, and lab tours. By providing a first-hand view of leading-edge research at a time when students are actively weighing career directions, ISSYP has helped catalyze many scientific careers. Moreover, ISSYP showcases Canada's vibrant science community to some of the world's most promising science students, and a significant number of ISSYP alumni go on to study at Canadian universities.

In 2009-10, PI Outreach continued to emphasize the 'quality over quantity' approach which was piloted last year: selecting top students who have already shown a strong affinity and talent for science. In August 2009, ISSYP was held very successfully with 37 participants and included a visit to the Sudbury Neutrino Observatory (SNOLAB), an underground facility specializing in neutrino and dark matter

physics; the visit was deemed so successful that it was repeated in the 2010 edition. In July 2010, ISSYP delivered two weeks of high-level enrichment to 40 students selected from 16 countries.

Go Physics! (New Initiative)

Go Physics! is a new initiative that delivers one-day intensive 'mini-ISSYP' camps to keen students in Grades 11 and 12 across Canada. The aims of the program are to extend the benefits of ISSYP to more students across the country without running numerous full-scale camps, which would be beyond the capacity of a small institution like PI. A total of six camps were held for approximately 30 students each time: two at PI, and one each in Vancouver, Winnipeg, Moncton and Fredericton. The program was successful, and is expected to continue, cycling between three and six per year (three camps to be held in major festival years) and will maintain a similar geographic distribution ratio.

Physica Phantastica Presentations

The *Physica Phantastica* series delivered scientifically rich and inspirational content to over 6,000 youth, including presentations to students who travelled from across the province for the *Quantum to Cosmos* festival. The enrichment activities were also held at the Canada Wide Science Fair in Peterborough, Ontario, the Sci-Tech Fair in Toronto, Ontario, and at UBC in Vancouver, BC. New content was also tested and introduced to intermediate level students, as the *Alice & Bob* 60-second animated science clips (see below) were incorporated into a rich presentation highlighting the power of critical thinking and scientific ideas.

'I Love Science' Youth Video Contest

The 'I Love Science' video contest challenged youth to use their creative genius and, in 30 seconds or less, to explain why they love science in thought-provoking and entertaining ways. Over 60 entries were received from students between the ages of 14 and 19 across Canada. Two grand prize winners received all-expenses paid round trips to Perimeter Institute in Waterloo, Ontario, and were part of the special "Hawking at the Perimeter" outreach broadcast, featuring Professor Stephen Hawking, on June 20, 2010, thereby saluting youth and their interest in science and technology.

Online Resources

PI Outreach offers online materials to share the power of theoretical physics with audiences of all ages and to serve as a model of outreach excellence. Many of the activities described above are digitized and appear online. *Virtual ISSYP,* for example, provides 'best of' content from the student summer camps, for the benefit of youth the world over. Other online resources include:

Power of Ideas

The *Power of Ideas* interactive digital experience demonstrates how discoveries and unifications in physics have advanced our world. For example, it shows how the apparently unconnected ideas of waves and particles were unified by quantum mechanics to explain how atoms can exist in our universe, ideas which have in turn become the basis of enormously powerful technologies. The online resource is grounded in the pedagogic principles of e-learning, enabling PI to share our resources with educational communities across Canada and beyond.

Alice and Bob in Wonderland

This series of catchy one-minute animations features the adventures of *Alice & Bob in Wonderland.* These nine viral videos, created for junior and intermediate level students, were designed to stimulate questions in young viewers and encourage them to use their reasoning abilities to try to answer them. The series has proven extremely popular, drawing over 3,000 web hits a month. The project's next phase will develop classroom-ready resources around each animation over the next three years.

Meet a Scientist

Over 30 *Meet a Scientist* video interviews are now accessible on the website, providing curious youth with personal insights from researchers who share their motivations and passions for a life in science. Many of the clips link to related PI resources, including "What We Research" and "PI Public Lectures," where viewers can access more detailed information on specific topics.

Webinars

PI Outreach undertook a pilot study into Webinar digital technology, evaluating its effectiveness as a vehicle to increase our impact among teachers in remote Canadian regions and to provide a method to grow PI's reach internationally while economizing resources. Six online workshops were given to participating educators in Alberta, Saskatchewan, Manitoba, and Ontario. The pilot's success has prompted further investigation in the coming year in order to maximize the reach of PI outreach content. The program will also investigate having PI researchers (PSI and graduate students, postdocs, faculty) participate in some webinars.

Programs for the General Public

Quantum to Cosmos: Ideas for the Future Festival (October 15-25, 2009)

The *Quantum to Cosmos* (Q2C) festival was one of PI's great successes of the last year. It was held to mark the Institute's tenth anniversary, to contribute to Canada's National Science and Technology Week, and to help celebrate the International Year of Astronomy. The 10-day science festival attracted 40,000 on-site and one million TV and online viewers, and included:

- 30 talks and panel discussions given by 79 leading scientists, journalists and innovators;
- Six "Science in the Pub" events;
- A science-inspired film festival;
- 5,000 square feet of exhibitions and presentations, including demonstrations, hands-on activities, physics experiments, an immersive 3D tour of the universe narrated by Stephen Hawking, and a scale model of the next Mars rover;
- Five nights of science and technology discussions on TVO's "The Agenda with Steve Paikin" broadcast live across Canada from PI's atrium.

The festival provided a national and international stage to share the power of ideas and PI's brand of excellence, and it is fair to say that it set a new standard for science festivals in Canada and beyond. Moreover, it attracted new and sufficient funding to break even. Media and blog coverage, as well as feedback from formal surveys conducted by PI, was overwhelmingly positive. There were many informal endorsements as well, including a letter from a grade 12 student who wrote to say that after visiting Q2C, she and some of her peers hosted their own "Science Play Day" for grade 9s and 10s to "encourage them to take science after grade 10."

For its next large-scale event, PI is working with the University of Waterloo and other partners to organize the Waterloo Global Science Initiative (WGSI). In June 2011, WGSI will bring scientists, the media, and young people together to address pressing global energy challenges through the collaborative and scientific lens PI Outreach is known for.

The Quantum Tamers: Revealing Our Weird and Wired Future Broadcast Documentary

PI's interactions with leading scientists, its experience in sharing abstract ideas in highly visual forms, and its fruitful partnerships with broadcast experts carried one outreach project into primetime over the last year. A highly collaborative team managed to share the complexities of quantum mechanics and quantum information through an entertaining made-for-TV documentary called *The Quantum Tamers: Revealing Our Weird & Wired Future.* This program for general audiences takes viewers deep inside the sewers of Vienna (the site of groundbreaking quantum teleportation experiments) and into cutting-edge quantum computing labs. Over a dozen leading scientists, including Stephen Hawking, took part in the

production in order to introduce concepts such as superposition and entanglement in novel ways that include the use of animation and even dancers.

The Quantum Tamers has been distributed globally to television networks and educational groups, and viewed in over 60 countries (and growing). It has also won four international awards: *Le Prix Audace* (the Audacity Prize) for "best originality in subject matter and treatment" at the Pariscience International Film Festival; *Best of Show* for TV feature documentary at The Accolades in California; the *Grand Jury Award for Best Documentary* at the DC Independent Film Festival in Washington; and the *Golden Palm Award* at the Mexico International Film Festival for "excellent and outstanding filmmaking."

Public Lecture Series

PI's flagship Public Lecture Series continued its tradition of presenting engaging talks to large and appreciative audiences. Once again, all of the lectures were sold out within minutes (the lectures are free, but require tickets ordered through PI's online system), filling the 600-seat theatre to capacity. In order to maximize the success of the public lectures, the events are professionally recorded and shared with wider audiences via broadcast on partnering television and cable stations as well as on demand viewing over Perimeter's website. In particular, TVO's "Big Idea" series broadcasts the lectures to national audiences via two satellite channels.

'Hawking at the Perimeter' Televised Broadcast

During his six-week visit to PI in June-July 2010, PI DRC Professor Stephen Hawking took part in the Institute's award-winning outreach program by delivering a special broadcast on TVO, viewable across Canada. The broadcast included opening remarks and welcomes from the Honourable Tony Clement, Minister of Industry, and also included the introduction of grand prize winners of the pan-Canadian 'I Love Science' youth video contest. The program initially aired on June 20, 2010 on TVO at 8 pm EDT to over 100,000 viewers nationally, and went on to gain larger audiences via re-broadcasts on TVO and CPAC in English and French that were tied to time zoned playbacks across the country. As a companion to the June 20 broadcast, Damian Pope, PI Senior Manager of Scientific Outreach, took part in a live blog discussion hosted on TVO's website and provided scientific context for Professor Hawking's talk.

Media Engagement and Professional Development

PI recognizes the value of professional development of journalists and is aware that raising the quality of reporting in the media can improve science literacy among the broader public. As such, PI has strong relationships with various science communication and science journalism organizations as well as science media outlets and programs with which the Institute collaborates and provides programming content.

During 2009-10, PI co-produced an episode of CBC Radio's *Quirks & Quarks* on the "top unanswered questions in physics." The resulting broadcast has been heard by over 1 million CBC listeners via repeat broadcasts and podcast downloads.

PI continued to support professional development for science journalists through continued support for the Science Communication program at the Banff Centre. The Institute also participated in planning phases of the new Science Media Centre of Canada, and is now a Charter Member.

Building on PI's existing relationship with the World Federation of Science Journalists (WFSJ), the Institute began planning one plenary session on "Science as a Force for Change" and two panel sessions for the upcoming World Conference of Science Journalists (WCSJ) to be held in Cairo, Egypt in 2011. Sessions such as these provide leading, international journalists with background information of value to future stories, while building important contacts with PI's scientific experts and staff.

Objective 9: Create the ultimate environment and infrastructure to support excellence in theoretical physics research

Summary of Achievements

- Continued construction of the *Stephen Hawking Centre at Perimeter Institute,* progressing on time and on budget for completion in fall 2011; the project received Ontario's first 'Gold Seal' distinction for construction quality and is on track to attaining LEED Silver certification for environmentally sustainable building;

- Commenced a major overhaul and expansion of IT systems and services; hired a Chief Information Officer (CIO) and initiated a search for a Scientific IT Specialist;

- Substantially expanded PI's library holdings;

- Increased wheelchair accessibility of PI's main building;

- Implemented greening policies to use less paper, increase recycling and composting, and decrease energy use.

Highlights

The Stephen Hawking Centre at Perimeter Institute

Now under construction, and scheduled to open in fall 2011, the *Stephen Hawking Centre at Perimeter Institute* (SHC) is a 55,000 square foot addition to PI's primary facility that has been conceived to house and create the optimal environment for theoretical research and training worldwide.

The SHC will more than double research and training space as PI's scientific community and outreach activities grow to critical mass. Designed by Governor General Award-winning Teeple Architects, the SHC will enable PI to accommodate 250 scientists and research trainees, all under one roof and operating as a single community. As part of PI's strategic effort to accelerate research, the SHC will provide state-of-the-art IT infrastructure and services, including remote conferencing, advanced data analysis and visualization tools, and the provision of in-house scientific computing expertise (see below).

Ontario's Ministry of Research and Innovation (MRI) and the Canada Foundation for Innovation (CFI) have provided a total of $20.8 million toward the expansion, which has been matched by private funds raised by the Institute. The SHC project has created approximately 250 jobs locally and was certified as Ontario's first-ever 'Gold Seal project,' a national award for high quality construction. Using the latest

environmentally sustainable building practice, the SHC is on track to LEED Silver certification. Discussions have also commenced with Christie Digital about the donation and installation of state-of-the-art visual display systems for the SHC.

Expansion of IT Services and Infrastructure

While the chalkboard remains the iconic tool of theoretical physics, the rapidly increasing power of both stand-alone computers and large grid architectures enable theorists to tackle not only numerical, but also analytical problems which were previously beyond reach. For example, using sophisticated algorithms developed by mathematicians, physicists and computer scientists, today's theorists can now study how black holes form, collide, and emit gravitational waves.

PI has led the field in the use of information technologies to share research through the development of the Perimeter Institute Recorded Seminar Archive (PIRSA), which shares virtually all seminars and conferences at PI over the Internet (see Objective 7).

As an integral part of the SHC project, PI has developed a strategy to fully realize the potential of advanced computing to accelerate theoretical physics research by: (i) appointing outstanding computational specialists, (ii) forging links to existing high performance computing resources, (iii) utilizing, developing and testing cutting-edge IT tools and sharing the results with the wider community, and (iv) upgrading PIRSA, Perimeter's online seminars archive.

As part of this strategy, two new positions have been created. In February 2010, a Chief Information Officer was appointed to develop and implement ICT strategies, policies, practices and services that will facilitate the achievement of the Institutes' research, training and outreach objectives. Following a needs assessment, a hybrid research/IT position combining advanced knowledge of physics research with IT expertise has been created, and recruitment is underway.

Library Expansion

In 2009-10, the PI Library continued to expand its print collection as part of a comprehensive strategy to become a well-resourced centre for resident and visiting researchers. The strategy includes strengthening the resource collections, providing secure access to electronic resources through formalized agreements, providing a user-friendly work/research environment, and expanding traditional library services. Over the last year, the PI Library added 827 new texts, bringing the total to 3,768 in the print collection. By 2014, the library will house over 5,000 volumes. The result will be a well-rounded collection including new and classic reference texts which fully represent the subject areas at PI and supporting disciplines.

Expanding the Perimeter

PI is grounded upon an innovative public-private partnership which shares the opportunities, benefits, and responsibility for long-term investment in fundamental research—the type of research that produces the conceptual breakthroughs needed for creating radically new technologies.

Sustained public investments in PI have been critical to the Institute's achievements to date. PI seeks to continue this highly successful relationship with the public sector while attracting increasing private investment. In order to ensure the Institute's long-term sustainability as it grows toward becoming a world leading centre in theoretical physics, PI recognizes that it must expand its base of financial support. To this end, the Institute has embarked on a major fundraising campaign, *Expanding the Perimeter*.

Jon Dellandrea, a noted advancement professional, is leading the campaign, supported by a small staff. A Leadership Council, led by PI Founder and Board Chair Mike Lazaridis, and Board Vice-Chair, Cosimo Fiorenza, has been constituted, and several influential leaders, mainly from the private sector, have joined. This council will in turn engage their wider circle of contacts in order to obtain their financial participation in PI's vision.

In conjunction with this campaign, continued public investment in PI will ensure the Institute's long-term viability, while growing and sustaining an incalculable strategic asset for Canada: a globally unique research community of unprecedented strength, a leader in the most ambitious, high potential payoff research, a magnet for top scientific talent globally, and an unparalleled research training ground for the future.

Overview of Financial Statements, Expenditures, Criteria and Investment Strategy

PERIMETER INSTITUTE

SUMMARIZED FINANCIAL STATEMENTS

JULY 31, 2010

ZEIFMANS LLP
CHARTERED ACCOUNTANTS

ZEIFMANS LLP
CHARTERED ACCOUNTANTS

201 Bridgeland Avenue
Toronto, Ontario M6A 1Y7
Tel: (416) 256-4000
Fax: (416) 256-4001
Email: info@zeifmans.ca
www.zeifmans.ca

AUDITORS' REPORT

To the Directors of
Perimeter Institute

The accompanying summarized statements of financial position and operations and changes in fund balances are derived from the complete financial statements of Perimeter Institute as at July 31, 2010 and for the year then ended on which we expressed an opinion without reservation in our report dated September 24, 2010. The fair summarization of the complete financial statements is the responsibility of management. Our responsibility, in accordance with the applicable Assurance Guideline of The Canadian Institute of Chartered Accountants, is to report on the summarized financial statements.

In our opinion, the accompanying financial statements fairly summarize, in all material respects, the related complete financial statements in accordance with the criteria described in the Guideline referred to above.

These summarized financial statements do not contain all the disclosures required by Canadian generally accepted accounting principles. Readers are cautioned that these statements may not be appropriate for their purposes. For more information on the entity's financial position, results of operations and cash flows, reference should be made to the related complete financial statements.

Zeifmans LLP

Toronto, Ontario
September 24, 2010

Chartered Accountants
Licensed Public Accountants

PERIMETER INSTITUTE
(Incorporated Under the Laws of Canada Without Share Capital)
SUMMARIZED STATEMENT OF FINANCIAL POSITION
AS AT JULY 31, 2010

ASSETS

	2010					2009
	Restricted Funds					
	Long-term Endowment	Capital Asset	Research and Outreach	Operating Fund	Total	Total
Current assets:						
Cash and cash equivalents	$ 2,256,011	$ ---	$ 2,807,138	$ ---	$ 5,063,149	$ 4,270,695
Investments	209,002,595	---	---	---	209,002,595	207,877,993
Government grants receivable	---	3,571,299	40,000	---	3,611,299	5,072,000
Other current assets	---	---	716,748	452,801	1,169,549	1,476,919
	211,258,606	3,571,299	3,563,886	452,801	218,846,592	218,697,607
Other receivable	---	---	29,938	---	29,938	57,024
Property and equipment	---	38,197,202	---	---	38,197,202	28,656,950
TOTAL ASSETS	$ 211,258,606	$ 41,768,501	$ 3,593,824	$ 452,801	$ 257,073,732	$ 247,411,581

LIABILITIES AND FUND BALANCES

Current liabilities:						
Bank indebtedness	$ ---	$ ---	$ ---	$ ---	$ ---	$ 3,275,000
Accounts payable and other current liabilities	---	3,654,105	1,262,497	---	4,916,602	1,959,209
TOTAL LIABILITIES	---	3,654,105	1,262,497	---	4,916,602	5,234,209
Fund balances:						
Invested in capital assets	---	38,114,396	---	---	38,114,396	28,069,304
Externally restricted	133,848,828	---	2,331,327	---	136,180,155	131,019,937
Internally restricted	77,409,778	---	---	---	77,409,778	82,903,934
Unrestricted	---	---	---	452,801	452,801	184,197
TOTAL FUND BALANCES	211,258,606	38,114,396	2,331,327	452,801	252,157,130	242,177,372
	$ 211,258,606	$ 41,768,501	$ 3,593,824	$ 452,801	$ 257,073,732	$ 247,411,581

On behalf of the Board:

_____ Director

_____ Director

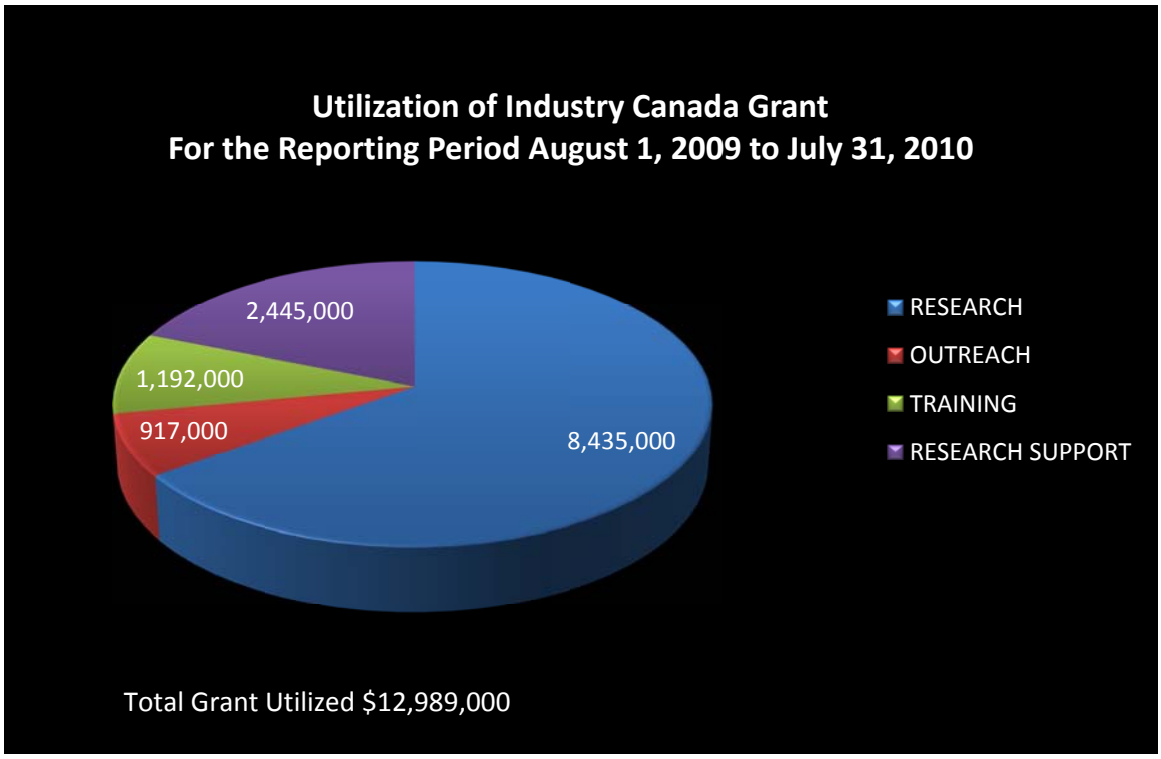
ZEIFMANS LLP
CHARTERED ACCOUNTANTS

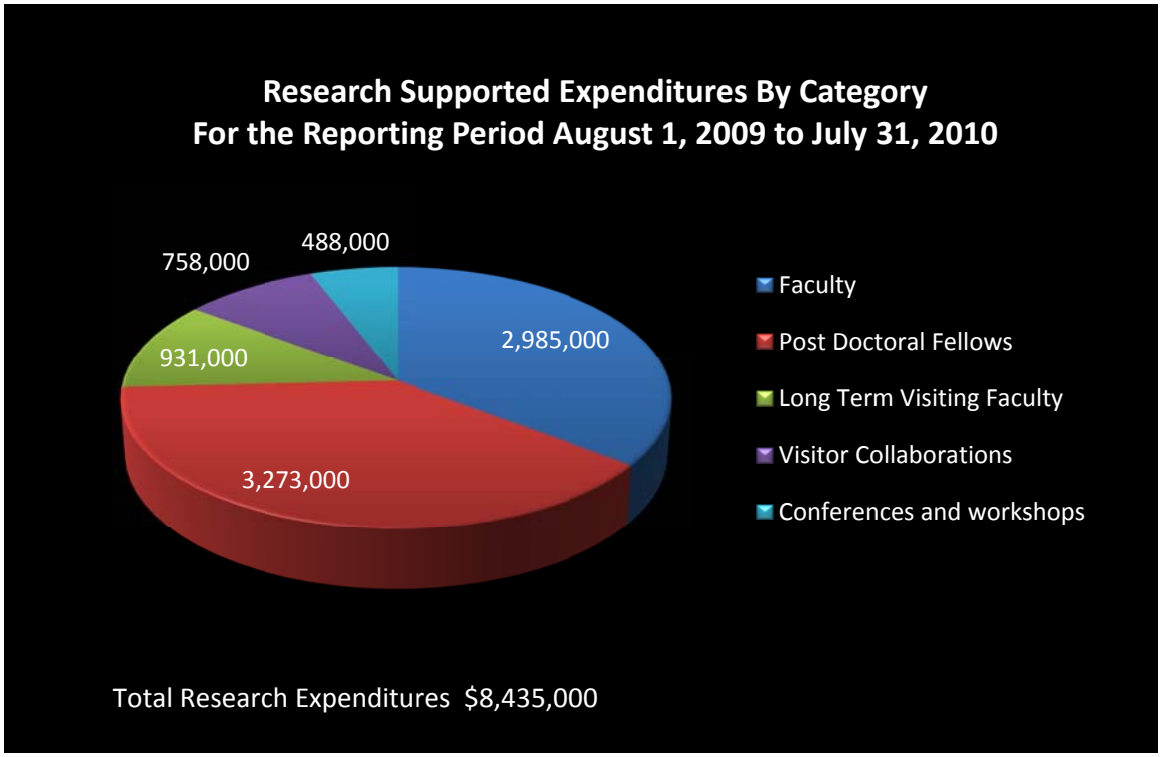
PERIMETER INSTITUTE
SUMMARIZED STATEMENT OF OPERATIONS AND CHANGES IN FUND BALANCES
FOR THE YEAR ENDED JULY 31, 2010

	2010					2009
	Restricted Funds					
	Long-term Endowment	Capital Asset	Research and Outreach	Operating Fund	Total	Total
Revenue:						
Government grants	$ ---	$ 7,598,439	$ 10,474,200	$ ---	**$ 18,072,639**	$ 5,588,200
Donations	---	---	---	625,753	**625,753**	40,087,038
Other income	---	---	435,366	---	**435,366**	125,000
	---	7,598,439	10,909,566	625,753	**19,133,758**	45,800,238
Expenditures:						
Research	---	1,636	11,238,989	67,468	**11,308,093**	9,643,807
Outreach	---	---	3,130,445	18,273	**3,148,718**	3,151,042
Indirect research and operations	---	---	4,289,711	124,872	**4,414,583**	3,706,447
Total operating expenditures	---	1,636	18,659,145	210,613	**18,871,394**	16,501,296
Excess of revenue over expenses (expenses over revenue) before investment income (loss) and amortization	---	7,596,803	(7,749,579)	415,140	**262,364**	29,298,942
Amortization	---	(1,656,934)	---	---	**(1,656,934)**	(1,763,308)
Investment income (loss)	3,988,842	---	---	7,385,486	**11,374,328**	(49,432,440)
Excess of revenue over expenses (expenses over revenue)	3,988,842	5,939,869	(7,749,579)	7,800,626	**9,979,758**	(21,896,806)
Fund balances, beginning of year	212,763,920	28,069,304	1,159,951	184,197	**242,177,372**	264,074,178
	216,752,762	34,009,173	(6,589,628)	7,984,823	**252,157,130**	242,177,372
Interfund transfers	(5,494,156)	4,105,223	8,920,955	(7,532,022)	---	---
Fund balances, end of year	$ 211,258,606	$ 38,114,396	$ 2,331,327	$ 452,801	**$ 252,157,130**	$ 242,177,372

ZEIFMANS LLP
CHARTERED ACCOUNTANTS

Expenditures by Activity





Criteria Applied to Eligible Activities

Perimeter Institute uses 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. Tools used to measure outcomes, results, and impact include:

Performance Monitoring – Internal

- Annual Reports on research activity submitted to the Director by all researchers for evaluation
- Annual Reports on research activity submitted to the Director by all research groups for evaluation
- Ongoing monitoring of publication and citation records
- Monthly updates and monitoring of progress of all scientific programs
- Post-conference reports and evaluation
- Annual evaluation of all scientific programs
- Mid-term researcher performance reviews
- Postdoctoral Fellow and junior Faculty mentorship program
- Visitor research activity reports and on-going tracking of all output
- Monitoring of Postdoctoral Fellow post-PI placement success
- Monitoring of international researcher presence and impact through collaborations and invitations to lecture
- Internal review and evaluation of all outreach programs and products

Performance Monitoring – External

- Annual reporting to international Scientific Advisory Committee with subsequent performance assessment and recommendations. The Committee consists of the following members: Gerard Milburn, chair; Abhay Ashtekar; Sir Michael Berry; Matthew Fisher; Brian Greene(to begin Sept. 2010); Gerard ‘t Hooft; Igor Klebanov; Renate Loll (to begin Sept. 2010); Michael Peskin; John Preskill; David Spergel; Erik Verlinde (to begin Sept. 2010); and Brigitta Whaley (to begin Sept. 2010)
- Review by the Scientific Advisory Committee of all Faculty and Associate Faculty hires, renewals, and promotions
- Peer review of publications
- Performance audits as per granting agreements
- External review and evaluation process of all outreach programs and products

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 operations 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 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 D, PI Board of Directors).

Financial planning, accountability, and investment strategy are carried out by the Board's Investment Committee and its Finance and Audit Committee. The Board also forms other committees as required to assist it in discharging its duties. Reporting to the Board of Directors, the Executive 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 Executive Director and is in charge of day-to-day operations of the Institute. Support for the COO is provided by a team of senior directors and 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. Committee chairs report to the Executive Director.

The international Scientific Advisory Committee (SAC) is an integral oversight body, deliberately created to assist the Board of Directors and Executive Director to ensure objectivity and a high standard of scientific excellence. The SAC meets on an annual basis and submits detailed reports with

recommendations to the Board and Executive Director following each meeting. The SAC is composed of eminent scientists drawn from the international community (see Appendix E, SAC Members).

Financial – Investment and Management of Funds

The Board of Directors of Perimeter Institute is supported in fulfilling its fiduciary responsibilities with respect to financial management 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.

Objectives for 2010-11

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, 2010-11

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 create the world's best environment and infrastructure for theoretical physics research, training and outreach through completion of *The Stephen Hawking Centre at Perimeter Institute*

Objective 4: To generate a flow-through of the most promising talent

Objective 5: To become the second 'research home' for many of the world's outstanding theorists

Objective 6: To act as a hub for a network of theoretical physics centres around the world

Objective 7: To increase PI's role as Canada's focal point for foundational physics research

Objective 8: To host timely, focused conferences, workshops, seminars and courses

Objective 9: To engage in high impact outreach

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

Appendix A: Perimeter Institute Faculty

Faculty

Neil Turok is the Director and a senior Faculty member at Perimeter Institute. He earned his PhD at Imperial College, held a postdoctoral fellowship in Santa Barbara, and was an Associate Scientist at Fermilab before moving to Princeton University, where he became Professor of Physics in 1994. In 1997, he was appointed to the Chair of Mathematical Physics in the Department of Applied Mathematics and Theoretical Physics (DAMTP) at the University of Cambridge. In October 2008, he joined Perimeter Institute as its Director. Among his many honours, Professor Turok was awarded Sloan and Packard Fellowships and the 1992 James Clerk Maxwell medal of the UK Institute of Physics. Professor Turok has worked in a number of areas of theoretical physics and cosmology, focusing on developing fundamental theories and new observational tests. In the early 1990s, his group showed how the polarization and temperature anisotropies of the cosmic background radiation would be correlated, a prediction confirmed in detail by recent precision measurements. The team also developed a key test for the presence of the cosmological constant, also recently confirmed. With Stephen Hawking, he later developed the Hawking-Turok instanton solutions describing the birth of inflationary universes. More recently, with Paul Steinhardt at Princeton, 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 2006, Steinhardt and Turok showed how the model naturally allowed the cosmological constant to relax to very small values, consistent with current observations. Steinhardt and Turok co-authored the popular science book *Endless Universe: Beyond the Big Bang*. In 2009, Professor Turok was named a Canadian Institute for Advanced Research (CIFAR) Fellow in the cosmology and gravitation program. Born in South Africa, Professor Turok founded the African Institute for Mathematical Sciences (AIMS), which opened in 2003. Based in Cape Town, this postgraduate educational centre supports the development of mathematics and science across the African continent (see www.aims.ac.za and www.nexteinstein.org). For this work and his contributions to theoretical physics, he was awarded the TED Prize (www.ted.com) and a "Most Innovative People" award at the 2008 World Summit on Innovation and Entrepreneurship (WSIE).

Latham Boyle joined PI as a junior Faculty member in 2010. He received his PhD in physics in 2006 from Princeton University, under the direction of Paul Steinhardt. From 2006-2009, Dr. Boyle held a Canadian Institute for Theoretical Astrophysics (CITA) Postdoctoral Fellowship; he is also a Junior Fellow of the Canadian Institute for Advanced Research (CIFAR). Dr. Boyle has studied what gravitational wave measurements can teach us about the beginning of the universe; with Paul Steinhardt, he derived a series of "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 has been a Faculty member at PI since 2005. He received his PhD from Harvard in 2002. From 2002-2005, he was a Member of the School of Natural Sciences at the Institute for Advanced Study in Princeton, New Jersey, USA. Dr. Cachazo is one of the world's leading experts in the subject of the study and computation of scattering amplitudes in quantum chromodynamics (QCD) and N=4 super Yang-Mills (MSYM) theories. In 2007, he was awarded an Early Researcher Award for his project "Taming the Strong Interactions: Perturbative and Non-Perturbative Methods." In 2009, he was awarded the Gribov Medal of the European Physical Society, "for work that has led to significant simplifications in the calculation of scattering amplitudes in both gauge theories and gravity ones."

Laurent Freidel received his PhD from L'École Normale Superieure de Lyon in 1994. He has made many notable contributions in the field of quantum gravity and joined Perimeter Institute in September 2006. Dr. Freidel is a mathematical physicist with outstanding knowledge of a wide range of areas including integrable systems, topological field theories, 2d conformal field theory and QCD (quantum chromodynamics). He has authored or co-authored over 40 publications, many of which are known among fellow researchers for offering particularly complete, detailed arguments. Dr. Freidel is also the author or co-author of several significant papers on spin foam models – higher-dimensional diagrams that operate as models of the quantum geometry of spacetime in loop quantum gravity. He also contributes to further research on the low energy limit of spin foam models including new proposed formulations and coupling to matter. Dr. Freidel has held positions at Penn State University and L'École Normale and has been a member of France's Centre National de la Recherche Scientifique (CNRS) since 1995. Dr. Freidel is also the recipient of several awards including two ACI-Blanche grants in France.

Jaume Gomis received his PhD from Rutgers University in 1999, before working at the California Institute of Technology as a Postdoctoral Scholar and as the Sherman Fairchild Senior Research Fellow. In 2004, Dr. Gomis was awarded a European Young Investigator Award by the European Science Foundation, which he declined in order to join Perimeter Institute that same year. His main areas of expertise are string theory and quantum field theory. In 2009, Dr. Gomis was awarded an Early Researcher Award from the Ministry of Research and Innovation of Ontario for his project "New Phases of Matter and String Theory," aimed at developing new techniques for describing quantum phenomena in nuclear and particle physics.

Daniel Gottesman received his PhD in 1997 from the California Institute of Technology, where he was a student of John Preskill. He then held postdoctoral positions at Los Alamos National Lab, Microsoft Research, and UC Berkeley (as a long-term CMI Prize Fellow for the Clay Mathematics Institute). Dr. 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. His 41 papers have attracted well over 3,500 citations to date. He is also a Fellow in CIFAR's Quantum Information Processing program.

Lucien Hardy received his PhD at Durham University in 1992 under the supervision of Euan Squires. Prior to his arrival at PI, he held research and lecturing positions at various European universities including the University of Oxford (1997-2002), La Sapienza University, Rome, Italy (1996-1997), the University of

Durham, UK (1994-1996), University of Innsbruck, Austria (1993-1994), and the National University of Ireland (1992-1993). While in Rome, he collaborated on an experiment to demonstrate quantum teleportation. 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.

Fotini Markopoulou received her PhD from Imperial College in 1998 under the supervision of Christopher Isham. She joined PI as one of its first Faculty members in 2001, prior to which she held postdoctoral positions at the Albert Einstein Institute (2001-2002), Imperial College London (1999-2000), and Penn State University (1997-1999). Dr. Markopoulou is a past recipient of First Prize in the Science and Ultimate Reality Young Researchers Competition in honour of J.A. Wheeler (2001). She has been a visiting professor at MIT (2008), and currently holds an Alexander von Humboldt Fellowship for Experienced Researchers at the Albert Einstein Institute in Germany.

Robert Myers is one of the leading theoretical physicists working in the area of string theory in Canada. He received his PhD from Princeton University in 1986, after which he was a postdoctoral researcher at the Kavli Institute for Theoretical Physics at the University of California, Santa Barbara. He moved to McGill University in 1989, where he was a Professor of Physics until moving to Perimeter Institute in the summer of 2001. Currently, he also holds an Adjunct position in the Department of Physics and Astronomy at the University of Waterloo. Dr. Myers was awarded the Herzberg Medal in 1999 by the Canadian Association of Physicists for seminal contributions to our understanding of black hole microphysics and D-branes. He won the 2005 CAP-CRM Prize, Canada's top prize in theoretical and mathematical physics, awarded by the Canadian Association of Physicists and the Centre de Recherches Mathématiques. In 2006, he was elected a Fellow of the Royal Society of Canada. Dr. Myers is also a Fellow of the Cosmology and Gravity Program of the Canadian Institute for Advanced Research. From 2001-2005, he was a founding member on the scientific advisory board of the Banff International Research Station. Dr. Myers also serves on the editorial boards of the research journals *Annals of Physics* and *Journal of High Energy Physics*.

Philip Schuster (to arrive September 2010) completed his PhD in 2007 at Harvard University under the supervision of Nima Arkani-Hamed, and was a Research Associate at SLAC National Accelerator Laboratory from 2007-2010. Dr. 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 a variety of theories that may be discovered at new experiments at the Large Hadron Collider (LHC) at CERN. In collaboration with members of the Compact Muon Solenoid (CMS) experiment at the LHC, he developed a set of methods to characterize potential new physics signals in a physically transparent manner that makes it easier to identify the underlying theory explaining these signals. He is also a co-spokesperson for the APEX collaboration, which is developing an electron fixed-target experiment designed to search for new forces at the GeV-scale with unrivalled sensitivity, and which recently completed a successful test run at the Thomas Jefferson National Accelerator Facility in Virginia.

Lee Smolin is one of Perimeter Institute's founding Faculty members. After acquiring an undergraduate degree in Natural Philosophy from Hampshire College, he received his PhD from Harvard University in

1979, after which he held postdoctoral positions at the Institute for Advanced Study, Princeton, the Institute for Theoretical Physics, Santa Barbara, and the Enrico Fermi Institute at the University of Chicago. He was a professor at Yale, Syracuse and Penn State Universities, and has held various visiting positions at Imperial College London, and the Universities of Oxford, Cambridge, Rome, Trento, and SISSA, in Italy. Professor Smolin's research is centered on the problem of quantum gravity, and was one of the initiators of two research programs: loop quantum gravity and deformed special relativity. He has also contributed to cosmology, the foundations of quantum mechanics, astrophysics, philosophy of science and, recently, economics, and his papers have generated over 6,390 citations to date. His three non-technical books, *The Life of the Cosmos*, *Three Roads to Quantum Gravity*, and *The Trouble With Physics*, explore philosophical issues raised by developments in modern physics and cosmology. They have been widely read by the public and translated into over 20 languages. In 2007, Professor Smolin was awarded the Majorana Prize and, in 2009, he was given the Klopsteg Memorial Award from the American Association of Physics Teachers for his "extraordinary accomplishments in communicating the excitement of physics to the general public." Professor Smolin is an elected Fellow of the American Physical Society and, in 2010, was elected as a Fellow of the Royal Society of Canada.

Robert Spekkens received his PhD from the University of Toronto in 2001, and subsequently held a postdoctoral fellowship at Perimeter Institute and an International Royal Society Fellowship at the University of Cambridge. He joined PI's Faculty in 2008. Dr. Spekkens' 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. He is a previous winner of the Birkhoff-von Neumann Prize of the International Quantum Structures Association.

Natalia Toro (to arrive September 2010) completed her PhD at Harvard in 2007 under the supervision of Nima Arkani-Hamed, a Distinguished Research Chair at Perimeter Institute, and subsequently completed a postdoctoral fellowship at Stanford University SITP. Dr. 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.

Pedro Vieira joined PI in 2009 from the Max Planck Institute for Gravitational Physics (Albert Einstein Institute) in Potsdam, Germany, where he was a Junior Scientist from 2008-2009. Dr. Vieira completed his PhD at the École Normale Supérieure Paris and the Centro de Fisica do Porto, Universidade do Porto, under the supervision of Vladimir Kazakov and Miguel Sousa Costa. Dr. Vieira's research concerns the development of new mathematical techniques for gauge and string theories, ultimately aiming toward the solution of a realistic four-dimensional gauge theory. Using integrability techniques, he and his collaborators have recently made significant progress in computing, for the first time, the exact (planar) spectrum of a remarkable holographic duality between a theory of gravity and field theory known as the

AdS/CFT correspondence. This work may yield new insights into both gauge theories and quantum gravity, and for theoretical calculations of scattering amplitudes in particle physics.

Associate Faculty

Niayesh Afshordi (jointly appointed with the University of Waterloo) completed his PhD at Princeton under the supervision of David Spergel in 2004. He was the Institute for Theory and Computation Fellow at the Harvard-Smithsonian Center for Astrophysics from 2004-2007, and a Distinguished Research Fellow at Perimeter Institute from 2008-2009. In 2010, Professor Afshordi joined PI as an Associate Faculty member, in a joint appointment with the Department of Physics and Astronomy at the University of Waterloo. Professor Afshordi specializes in interdisciplinary problems in fundamental physics, astrophysics, and cosmology, with particular focus on observational findings that can help address problems in fundamental physics. In 2010, Professor Afshordi was awarded a Discovery Accelerator Supplement from the Natural Sciences and Engineering Research Council of Canada (NSERC), one of only eight awarded across Canada in physics. His 28 peer-reviewed publications have attracted over 900 citations to date.

Alex Buchel (jointly appointed with the University of Western Ontario) received his PhD from Cornell in 1999. He was a Postdoctoral Researcher at the Institute for Theoretical Physics, UCSB, US from 1999-2002, and a Research Fellow at the Michigan Center for Theoretical Physics, University of Michigan from 2002-2003. He joined PI's Faculty in 2003. Professor Buchel's research efforts focus on understanding the quantum properties of black holes and the origin of our universe, as described by string theory. Additionally, he is involved in developing analytical tools in string theory that could shed new light on strong interactions of subatomic particles. In 2007, Professor Buchel was awarded an Early Researcher Award from Ontario's Ministry of Research and Innovation.

Cliff Burgess (jointly appointed with McMaster University) received his PhD from the University of Texas at Austin in 1985 under the supervision of Steven Weinberg. From 1985-1987, he was a Member in the School of Natural Sciences at the Institute for Advanced Study in Princeton, New Jersey, and from 1987-2005, he was a Faculty member at McGill University, where he was named the James McGill Professor in 2003. In 2004, he joined PI's Faculty as an Associate member, and was jointly appointed to McMaster University's Faculty in 2005. Over two decades, Professor 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. He has authored several authoritative reviews of effective field theories, numerous book and encyclopedia chapters, and co-authored a graduate text on the Standard Model. From 2005-2007, Professor Burgess held a Killam Fellowship. In 2008, Professor Burgess was elected a Fellow of the Royal Society of Canada and, in 2010, he won the CAP-CRM Prize in Theoretical and Mathematical Physics, Canada's highest honour in theoretical physics.

Richard Cleve (jointly appointed with the University of Waterloo) received his PhD from the University of Toronto in 1989, specializing in computational complexity and cryptography. He completed a postdoctoral fellowship at Berkeley's International Computer Science Institute from 1988-1990, and joined the Faculty in the Department of Computer Science at the University of Calgary in 1990. In 2004, Professor Cleve joined PI and the Institute for Quantum Computing (IQC), where he holds the IQC Endowed Chair in Quantum Computing. He is cross-appointed as a Professor in the School of Computer Science at the University of Waterloo. Professor Cleve has made numerous important contributions to quantum algorithms and information theory. He is a Founding Fellow of the Canadian Institute for Advanced Research (CIFAR) Quantum Information Processing Program, and a team leader at QuantumWorks, Canada's national research consortium on quantum information science. He is a Founding Managing Editor of the journal *Quantum Information & Computation*. In 2008, Professor Cleve was awarded the Canadian Association of Physicists-Centre de Recherches en Mathématiques Prize in Theoretical and Mathematical Physics for his seminal contributions in quantum information science, and he was elected as a Fellow of the Royal Society of Canada in 2010.

David Cory (jointly appointed with the Institute for Quantum Computing and the Department of Chemistry at the University of Waterloo) received his PhD in physical chemistry from Case Western Reserve University in Cleveland, Ohio. He held postdoctoral fellowships at the University of Nijmegen, The Netherlands, and at the National Research Council at the Naval Research Laboratory in Washington, D.C. He was also a senior scientist at Bruker Instruments, and led their research and development activities in nuclear magnetic resonance. In 1992, he joined the Department of Nuclear Science and Engineering at MIT. Since 1996, Professor 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. From 2009-2010, Professor Cory was a Visiting Researcher at PI and, in 2010, he was named the Canada Excellence Research Chair in Quantum Information Processing. Professor Cory chairs the advisory committee for CIFAR's Quantum Information Processing program.

Adrian Kent (jointly appointed with the University of Cambridge) received his PhD from the University of Cambridge in 1996. Prior to joining PI's faculty, he was an Enrico Fermi postdoctoral fellow at the University of Chicago, a member of the Institute for Advanced Study in Princeton, New Jersey, and a Royal Society University Research Fellow at the University of Cambridge. Professor Kent's research is focused on the foundations of physics, quantum cryptography and quantum information theory, including the physics of decoherence and its implications for fundamental physics, novel tests of quantum theory and alternative theories, new cryptographic applications of quantum information, and new scientific applications of quantum information. He co-edited *Many Worlds? Everett, Quantum Theory and Reality,* published by Oxford University Press in 2010.

Raymond Laflamme (jointly appointed with the Institute for Quantum Computing, University of Waterloo) is a founding Faculty member of Perimeter Institute. He completed his PhD at the University of Cambridge under the direction of Stephen Hawking, and from 1988-90, he held a Killam postdoctoral fellowship at UBC, and then a research fellowship at Peterhouse College, University of Cambridge. From 1992-2001, Professor Laflamme worked as a research scientist at Los Alamos Research Laboratory,

where his interests shifted from cosmology to quantum computing. Since the mid-1990s, Professor Laflamme has elucidated theoretical approaches to quantum error correction. In work with Emmanuel Knill, he gave conditions for quantum error correcting codes, and established the fault-tolerance threshold, thereby showing that quantum computing systems could be useful even in the presence of noise. He then went on to perform the first experimental steps toward a demonstration of quantum error correction. With colleagues, he developed a blueprint for a quantum information processor using linear optics, and devised and implemented new methods to make quantum information robust against corruption in both cryptographic and computational settings. In 2001, Professor Laflamme was attracted back to Canada to become a founding member of Perimeter Institute and the founding Director of the Institute for Quantum Computing (IQC). Professor Laflamme is the Director of QuantumWorks, Canada's national research consortium on quantum information science, and has been Director of the Quantum Information Program at the Canadian Institute for Advanced Research (CIFAR) since 2003, and a CIFAR Fellow since 2001. Professor Laflamme holds the Canada Research Chair in Quantum Information, and is a Professor in the Department of Physics and Astronomy at the University of Waterloo.

Luis Lehner (jointly appointed with the University of Guelph) received his PhD from the University of Pittsburgh in 1998 under the direction of Jeffrey Winicour. He held postdoctoral fellowships at the University of Texas at Austin (1998-2000) and the University of British Columbia (2000-2002), and was an Assistant Professor of Physics at Louisiana State University from 2002-2006, before becoming an Associate Professor there from 2006-2009. He is currently an Adjunct Professor at LSU. Professor Lehner received the Honor Prize in 1993 from the National University of Cordoba, Argentina; held a Mellon pre-doctoral fellowship in 1997; won the CGS/UMI outstanding dissertation award and the Nicholas Metropolis award in 1999; and was a PIMS fellow from 2000-2002 and a CITA National Fellow in 2001-2002. He was an Alfred P. Sloan Fellow from 2003-2005 and is currently a CIFAR associate member, a fellow of the Institute of Physics, an editorial Board member of *Classical and Quantum Gravity* and a member of the NSF-Cyber Infrastructure User Advisory Committee.

Michele Mosca (jointly appointed with the University of Waterloo) obtained his DPhil in 1999 from the University of Oxford. He is a founding member of Perimeter Institute, and co-founder and the Deputy Director of the Institute for Quantum Computing. Professor Mosca has made major contributions to the theory and practice of quantum information processing, particularly in the areas of quantum algorithms, techniques for studying the limitations of quantum computers, quantum self-testing and private quantum channels. Together with collaborators at Oxford, he realized several of the first implementations of quantum algorithms using nuclear magnetic resonance. He has made major contributions to the phase estimation approach to quantum algorithms, including the hidden subgroup problems, and quantum searching and counting. In the area of quantum security, he helped define the notion of private quantum channels and develop optimal methods for encrypting quantum information using classical keys. His more recent work is focused on methods for testing untrusted quantum apparatus. Professor Mosca has won numerous academic awards and honours, including the Commonwealth Scholarship, the Premier's Research Excellence Award (2000-2005), and a Canada Research Chair in Quantum Computation (2002-2012). He has been a Canadian Institute for Advanced

Research (CIFAR) scholar since September 2003 and is a member of the University of Waterloo's Centre for Applied Cryptographic Research.

Ashwin Nayak (also appointed at the University of Waterloo) received his PhD in Computer Science from the University of California, Berkeley, in 1999. Subsequently, he held positions at DIMACS Center (Rutgers University) and AT&T Labs-Research, at the California Institute of Technology, and at the Mathematical Sciences Research Institute, Berkeley. Professor Nayak is an associate professor in the Department of Combinatorics and Optimization, and a member of the Institute for Quantum Computing at University of Waterloo. Professor Nayak was a recipient of an Early Researcher Award from the Ministry of Research and Innovation of Ontario in 2006, and a Discovery Accelerator Supplement from the Natural Science and Engineering Research Council (NSERC) of Canada in 2008.

Maxim Pospelov (jointly appointed with the University of Victoria) received his PhD from the Budker Institute of Nuclear Physics, Russia in 1994. He was the NATO Science Fellow at the University of Quebec in Montreal (1996-1998), a Research Associate at the University of Minnesota (1998-2001), a Visiting Scientist at McGill University (2001-2002), and an Advanced PPARC Research Fellow at the University of Sussex, UK (2002). In 2002, he joined the Department of Physics and Astronomy at the University of Victoria, and was cross-appointed to PI's faculty in 2004. Professor Pospelov works in the area of particle physics and has recently made detailed studies of Catalyzed Big Bang Nucleosynthesis (CBBN), a novel idea which he proposed to alleviate persistent discrepancy of theoretical predictions and experimental observations of lithium abundance in the universe.

Thomas Thiemann (jointly appointed with the Max Planck Institute for Gravitational Physics, Germany) received his PhD from RWTH Aachen University in 1993. His research centres on non-perturbative quantum field theory, in particular quantum gauge field theory and quantum gravity; non-perturbative aspects of quantum string theory; constructive and algebraic quantum field theory; Euclidean quantum field theory and its connection with statistical mechanics; semiclassical quantum field theory; and non-perturbative approximation methods. He is the author of *Modern Canonical Quantum General Relativity.*

Appendix B: PI Distinguished 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. Dr. Aharonov is on the faculty of Perimeter Scholars International.

Yakir Aharonov is a professor of theoretical condensed matter physics at Chapman University and Professor Emeritus at Tel Aviv University, as well as a Patron of Perimeter Scholars International. 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 member of the PSI faculty. 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.

Neta Bahcall is the Eugene Higgins Professor of Astrophysics at Princeton University. She is an observational cosmologist who has pioneered quantitative approaches to the understanding of astronomical data. These methods have enabled her to achieve key insights into such fundamental questions as the large-scale structure, mass, and fate of the universe, galaxy formation, the nature of quasars, and dark matter.

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 recently 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.

Gia Dvali is a Professor at New York University's Center for Cosmology and Particle Physics and a member of the Theory Division at CERN, in Switzerland. Professor Dvali investigates fundamental questions at the intersection between particle physics and cosmology, including large extra dimensions, quantum gravity, and the very early universe.

Stephen Hawking is the Emeritus Lucasian Professor of Mathematics at the Department of Applied Mathematics and Theoretical Physics at Cambridge. In his work, Dr. 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. Stephen Hawking has published three popular books; his best seller *A Brief History of Time* has sold over 30 million copies worldwide, and is the most popular scientific book of all time. Professor Hawking has 12 honourary 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 holds the Canada Research Chair in the Physics of Information at McGill University. His research focuses on finding efficient methods for performing the communication tasks that will be required for large-scale quantum information processing. This includes the development of methods for reliably sending quantum states through 'noisy' media and for protecting quantum information from unauthorized manipulation. He has also applied these techniques to the question of information loss from black holes. Among Dr. Hayden's honours, he is a past Alfred P. Sloan Foundation Fellow and Rhodes Scholar.

Christopher Isham is a Senior Research Investigator and Emeritus Professor of Theoretical Physics at Imperial College London. He is a former Senior Dean of the College. Dr. Isham has made many important contributions in the fields of quantum gravity and the foundations of quantum mechanics. Motivated by the "problem of time" in quantum gravity, he developed a new approach to quantum theory known as the "HPO formalism" that enables the theory to be extended to situations where there is no normal notion of time (such as in Einstein's theory of general relativity). Since the late 1990s, Dr. Isham has been developing a completely new approach to formulating theories of physics based on the mathematical concept of a "topos." This gives a radically new way of understanding the traditional problems of quantum theory as well as providing a framework in which to develop new theories that would not have been conceived using standard mathematics. From 2001-2005, Dr. Isham was a member of Perimeter Institute's Scientific Advisory Committee; in 2005, he was the Chair of the Committee.

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 National Medal of Science (US), 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. Dr. Kadanoff is on the faculty of Perimeter Scholars International.

Renate Loll is a Professor of Theoretical Physics and a member of the Institute for Theoretical Physics in the Faculty of Physics and Astronomy at Utrecht University. 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. She is also a Faculty member of Perimeter Scholars International.

Malcolm Perry is a Professor of Theoretical Physics in the Department of Applied Mathematics and Theoretical Physics at the University of Cambridge and a Fellow of Trinity College, Cambridge. His research centres upon general relativity, supergravity and string theory. Dr. Perry has made major contributions to string theory, Euclidean quantum gravity, and our understanding of black hole radiation. With Perimeter Institute Faculty member Robert Myers, he developed the Myers-Perry metric, which shows how to construct black holes in the higher spacetime dimensions associated with string theory. Dr. Perry's honours include an Sc.D. from the University of Cambridge. Dr. Perry is also on the faculty of Perimeter Scholars International.

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).

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."

Ashoke Sen, of the Harish-Chandra Research Institute in Allahabad, India, is a pioneering string theorist whose many contributions include the famous Sen Conjecture, as well as major insights about string dualities and entropy in black holes.

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.

Xiao-Gang Wen is the Cecil and Ida Green Professor of Physics in the department of Physics at MIT, and is also a member of the faculty of Perimeter Scholars International (PSI). He has proposed novel theories

about condensed matter physics, the nature of space-time, and superconductivity. His recent book, *Quantum Field Theory of Many-Body Systems*, explores many-particle quantum mechanics.

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.

Guifre Vidal is a Professor in the School of Physical Sciences at the University of Queensland and has made important contributions to the development of quantum information science, with applications to condensed matter theory. His research explores the phenomenon of entanglement, the renormalization group, and the development of tensor network algorithms to simulate quantum systems. Dr. Vidal's past honours include a Marie Curie Fellowship, awarded by the European Union, and a Sherman Fairchild Foundation Fellowship. He is a Federation Fellow of the Australian Research Council.

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 Alfred P. Sloan Foundation 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 C: Perimeter Institute Affiliate Members

Name	Institution	Research Area
Ian Affleck	University of British Columbia	Condensed Matter
Leslie Ballentine	Simon Fraser University	Quantum Foundations
Richard Bond	University of Toronto/CITA	Cosmology
Ivan Booth	Memorial University	General Relativity
Vincent Bouchard	University of Alberta	String Theory
Robert Brandenberger	McGill University	Cosmology
Gilles Brassard	University of Montreal	Quantum Information
Anton Burkov	University of Waterloo	Condensed Matter
Bruce Campbell	Carleton University	Particle Physics
Hilary Carteret	University of Calgary	Quantum Information
Jeffrey Chen	University of Waterloo	Condensed Matter
Andrew Childs	University of Waterloo	Quantum Information
Matthew Choptuik	University of British Columbia	Numerical General Relativity
Dan Christensen	University of Western Ontario	Quantum Gravity
Jim Cline	McGill University	Cosmology; Particle Physics
Alan Coley	Dalhousie University	General Relativity
Andrzej Czarnecki	University of Alberta	Particle Physics
Saurya Das	University of Lethbridge	Quantum Gravity
Arundhati Dasgupta	University of Lethbridge	Quantum Gravity
Keshav Dasgupta	McGill University	String Theory
Rainer Dick	University of Saskatchewan	Particle Physics
Joseph Emerson	University of Waterloo/IQC	Quantum Information

Name	Institution	Research Area
James Forrest	University of Waterloo	Polymer Physics
Doreen Fraser	University of Waterloo	Philosophy
Valeri Frolov	University of Alberta	Quantum Gravity; Gravitational Physics
Andrei Frolov	Simon Fraser University	Cosmology
Jack Gegenberg	University of New Brunswick	Quantum Gravity
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
Mike Hudson	University of Waterloo	Cosmology
Viqar Husain	University of New Brunswick	Quantum Gravity
Catherine Kallin	McMaster University	Condensed Matter
Joanna Karczmarek	University of British Columbia	String Theory
Gabriel Karl	University of Guelph	Particle Physics
Achim Kempf	University of Waterloo	Quantum Information
Pavel Kovtun	University of Victoria	String Theory
David Kribs	University of Guelph	Quantum Information
Gabor Kunstatter	University of Winnipeg	Quantum Gravity; Particle Physics
Sung-Sik Lee	McMaster University	Condensed Matter
Debbie Leung	University of Waterloo	Quantum Information
Randy Lewis	York University	Particle Physics

Name	Institution	Research Area
Hoi-Kwong Lo	University of Toronto	Quantum Information
Michael Luke	University of Toronto	Particle Physics
Norbert Lutkenhaus	University of Waterloo/IQC	Quantum Information
Alexander Maloney	McGill University	String Theory
Robert Mann	University of Waterloo	Quantum Gravity; Particle Physics
Gerard McKeon	University of Western Ontario	Particle Physics
Brian McNamara	University of Waterloo	Cosmology
Roger Melko	University of Waterloo	Condensed Matter
Volodya Miransky	University of Western Ontario	Particle Physics
Guy Moore	McGill University	Particle Physics
David Morrissey	TRIUMF Canada	Particle Physics
Norman Murray	University of Toronto/CITA	Astrophysics
Wayne Myrvold	University of Western Ontario	Philosophy
Julio Navarro	University of Victoria	Cosmology; Astrophyiscs
Elisabeth Nicol	University of Guelph	Condensed Matter
Garnet Ord	Ryerson University	Quantum Foundations
Maya Paczuski	University of Calgary	Quantum Information
Don Page	University of Alberta	Quantum Gravity; Gravitational Physics
Prakash Panangaden	McGill University	Quantum Foundations
Manu Paranjape	University of Montreal	Particle Physics
Amanda Peet	University of Toronto	String Theory
Ue-Li Pen	University of Toronto/CITA	Cosmology; Astrophysics

Name	Institution	Research Area
Harald Pfeiffer	University of Toronto/CITA	Numerical General Relativity
Levon Pogosian	Simon Fraser University	Cosmology
Eric Poisson	University of Guelph	Gravitational Physics
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	String Theory
Barry Sanders	University of Calgary	Quantum Information
Veronica Sanz	York University	Particle Physics
Kristin Schleich	University of British Columbia	General Relativity
Achim Schwenk	TRIUMF Canada	Particle Physics
Douglas Scott	University of British Columbia	Cosmology
Gordon Semenoff	University of British Columbia	String Theory; Particle Physics
Kris Sigurdson	University of British Columbia	Cosmology; Particle Physics
John Sipe	University of Toronto	Quantum Foundations; Condensed Matter
Philip Stamp	University of British Columbia	Condensed Matter
Aephraim Steinberg	University of Toronto	Quantum Optics
Alain Tapp	University of Montreal	Quantum Information
James Taylor	University of Waterloo	Cosmology
Mark Van Raamsdonk	University of British Columbia	String Theory

Name	Institution	Research Area
Mark Walton	University of Lethbridge	String Theory
John Watrous	University of Waterloo	Quantum Information
Steve Weinstein	University of Waterloo	Quantum Foundations; Philosophy
Lawrence Widrow	Queens University	Astrophysics
Frank Wilhelm	University of Waterloo	Quantum Information; Condensed Matter
Don Witt	University of British Columbia	Particle Physics; String Theory

Appendix D: Perimeter Institute Board of Directors

Mike Lazaridis, O.C., O.Ont., Chair, is Founder, President and Co-CEO of Research In Motion Limited (RIM). A visionary, innovator and engineer of extraordinary talent, he is the recipient of many technology and business awards. At RIM, Mr. Lazaridis leads R&D, product strategy and manufacturing for the world-renowned BlackBerry® wireless solution.

Donald W. Campbell is the senior strategy advisor at Davis LLP. Prior to joining Davis, he was Executive Vice-President of CAE Inc., where he led the company's world-wide government procurement activities. Mr. Campbell joined CAE after a distinguished career with Canada's Department of Foreign Affairs and International Trade, including serving as Canada's Ambassador to Japan.

Cosimo Fiorenza, Vice Chair and member of the Finance Committee, is the Vice-President and General Counsel of the Infinite Potential Group. He is actively involved at several public and private non-profit and charitable institutions in addition to Perimeter Institute, including the Law Society of Upper Canada, the Centre for International Governance Innovation, the Institute for Quantum Computing, and several private family foundations. Mr. Fiorenza holds a degree in Business Administration from Lakehead University and a law degree from the University of Ottawa.

Peter Godsoe, O.C., O.Ont., is a former Chairman of Scotiabank, from which he retired in March 2004. He holds a B.Sc. in Mathematics and Physics from the University of Toronto, an M.B.A. from the Harvard Business School, and is a C.A. and a Fellow of the Institute of Chartered Accountants of Ontario. Mr. Godsoe holds honourary degrees from University of King's College (1993), Concordia University (1995), University of Western Ontario (2001) and Dalhousie University (2004). In 2002, he became a member of the Canadian Business Hall of Fame and an Officer of the Order of Canada and in 2010 was honoured with the Order of Ontario. Mr. Godsoe remains active throughout a wide range of corporate boards and non-profit directorships.

Kevin Lynch is a distinguished former public servant with 33 years of service with the Government of Canada. Most recently, Dr. Lynch was the Clerk of the Privy Council, Secretary to the Cabinet and Head of the Public Service of Canada. His prior roles include Deputy Minister of Finance, Deputy Minister of Industry and an Executive Director with the International Monetary Fund.

Dr. Steve MacLean is 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 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.

John Reid is a Senior Partner with KPMG responsible for managing the Ontario Region. He mainly focuses on mergers and acquisitions, high technology and health care. Mr. Reid is the Chairman of the

Grand River Hospital Board of Directors and a member of the Board of Governors of Conestoga College of Applied Arts and Technology.

Appendix E: Perimeter Institute Scientific Advisory Committee

Gerard Milburn, Chair, University of Queensland (joined 2009). Professor Milburn's research interests include quantum optics, quantum measurement and stochastic processes, quantum information and quantum computation. He has published over 200 papers in international journals, with over 6,000 citations. He is also the author or co-author of several books, two of which seek to explain quantum phenomena and their potential for a general audience.

Abhay Ashtekar, Pennsylvania State University (joined 2008). Professor Ashtekar is Eberly Professor of Physics and the Director of the Institute for Gravitational Physics and Geometry at Pennsylvania State University. As the creator of Ashtekar variables, he is one of the founders of loop quantum gravity. He has written a number of descriptions of loop quantum gravity that are accessible to non-physicists.

Sir Michael Berry, University of Bristol (joined 2009). Sir Michael Berry is Professor Emeritus at Bristol University. He has made numerous important contributions to semi-classical physics (asymptotic physics, quantum chaos) applied to wave phenomena in quantum mechanics and other areas such as optics. Among other work, he is well-known for the Berry phase, a phenomenon which has found applications in atomic, condensed matter, nuclear, elementary particle physics, and optics. He was elected a fellow of the Royal Society of London in 1982, and was knighted in 1996. Sir Berry is a previous recipient of numerous honours and awards, including the Dirac Medals of both the Institute of Physics (1990) and the ICTP (1996), the Lilienfeld Prize (1990), the Wolf Prize (1998) and the London Mathematical Society's Polya Prize (2005). He is an elected member of numerous Physical Societies around the world and is presently Member of the Council of the Royal Society (UK) and Editor of *Proceedings of the Royal Society A*.

Matthew Fisher, California Institute of Technology (joined 2009). 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. In 1995, he received the Alan T. Waterman Award from the National Science Foundation, and has also been the recipient of the National Academy of Sciences Award for Initiatives in Research (1997). In 2003, he was elected as a Member of the American Academy of Arts and Sciences. Professor Fisher has over 150 publications.

Brian Greene, Columbia University (to begin September 2010). Brian Greene is 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 groundbreaking 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 *Icarus at the Edge of Time, A Children's Tale*. A three-part NOVA special based on *The Elegant Universe* won both the Emmy and Peabody Awards.

Gerard 't Hooft, Utrecht University (joined 2008). Professor 't Hooft's research focuses on gauge theories in elementary particle physics, quantum gravity and black holes, and fundamental aspects of quantum physics. In addition to the Ben Franklin Medal, Professor 't Hooft's contributions to science have been recognized with many awards, including the 1999 Nobel Prize in Physics, with the citation "for elucidating the quantum structure of electroweak interactions in physics."

Igor R. Klebanov, Princeton University (joined 2007). Professor Klebanov's research has touched on many aspects of theoretical physics and is presently centered on relations between superstring theory and quantum field theory. He is currently Thomas D. Jones Professor of Mathematical Physics at Princeton University. He has made many highly regarded contributions to the duality between gauge theories and strings.

Renate Loll, Utrecht University (to begin September 2010). Professor Loll is a Professor of Theoretical Physics and a member of the Institute for Theoretical Physics in the Faculty of Physics and Astronomy at Utrecht University. 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. Professor Loll is a Perimeter Institute Distinguished Research Chair and is also a lecturer in the Perimeter Scholars International program at the Institute.

Michael Peskin, Stanford Linear Accelerator Center (joined 2008). Professor Peskin's research interests include all aspects of theoretical elementary particle physics, but particularly the nature of new elementary particles and forces that will be discovered at the coming generation of proton and electron colliders. He was a Junior Fellow at the Harvard Society of Fellows from 1977-80 and was elected to the American Academy of Arts and Sciences in 2000. He is co-author of a popular textbook on quantum field theory.

John Preskill, California Institute of Technology (joined 2009). Professor Preskill is the Richard P. Feynman Professor of Theoretical Physics at the California Institute of Technology (Caltech). He is also the Director of the Institute for Quantum Information at Caltech, which he founded in 2000. Prior to joining the Caltech faculty in 1983, Professor Preskill was a Junior Fellow in the Harvard Society of Fellows and Associate Professor of Physics at Harvard, where he had received his PhD. Until the mid-1990s, Preskill's research focused on elementary particles, cosmology, and gravitation. His many contributions include work on superheavy magnetic monopoles in the early universe which led to the inflationary universe, the proposal that axions may comprise the universe's cold dark matter, and the theory of local discrete symmetries. Since the mid-1990s, his research has focused on mathematical

issues related to quantum computation and quantum information theory. Among his numerous honours, Professor Preskill is a past Alfred P. Sloan Fellow, a two-time recipient of the Associated Students of Caltech Teaching Award, an elected Fellow of the American Physical Society, and was the Morris Loeb Lecturer at Harvard University in 2006.

David Spergel, Princeton University (joined 2009). Professor Spergel is the Charles Young Professor of Astronomy at Princeton, as well as the Chair of the Department of Astrophysical Sciences. He is known for his work on the Wilkinson Microwave Anisotropy Probe mission. Professor Spergel is a MacArthur Fellow as well as a member of the US National Academy of Sciences. He is currently the chair of the Astrophysics Subcommittee of the NASA Advisory Council. He was co-awarded the 2010 Shaw Prize in Astronomy, along with Charles L. Bennett and Lyman A. Page Jr. for "leadership of the Wilkinson Microwave Anisotrophy Probe (WMAP) experiment, which has enabled precise determinations of the fundamental cosmological parameters, including the geometry, age and composition of the universe."

Erik Peter Verlinde, University of Amsterdam (to begin September 2010). Dr. 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, which include Verlinde algebra and the Verlinde formula, which are important in conformal field theory and topological field theory. His research centres on string theory, gravity, black holes and cosmology. He recently proposed a holographic theory of gravity which appears to lead naturally to the observed values of dark energy in the universe.

Birgitta Whaley, University of California, Berkeley (to begin September 2010). Dr. 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 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 aspects of quantum information science, quantum simulation of exotic topological phases and exploration of quantum effects in biological systems.