PERIMETER INSTITUTE
FOR THEORETICAL PHYSICS

2011-12 Annual Report to Industry Canada

Covering the Objectives, Activities, and Finances
for the period August 1, 2011 to July 31, 2012 and
Statement of Objectives for Next Year and the Future

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

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

Overview of Perimeter Institute

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

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

As of July 31, 2012, the Perimeter community has grown to include:

- 18 full-time Faculty
- 12 Associate Faculty
- 24 Distinguished Visiting Research Chairs
- 38 Postdoctoral Researchers
- 72 Graduate students[1]

As a major research hub, Perimeter's conference and visitor programs bring over 1,000 scientists to the Institute annually, catalyzing new research collaborations and discoveries across the spectrum of fundamental physics. Recognizing that many past breakthroughs have come from young scientists, the Institute puts a major emphasis on training the next generation of physicists.

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

[1] This includes 34 PhD students, 37 Perimeter Scholars International (PSI) master's students, and 1 master's student outside of the PSI program.

Contents

Executive Summary

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

Each of the Objectives set out in last year's Corporate Plan plays a part in the Institute's comprehensive long-term strategy for achieving this very ambitious goal. In 2011-12, the Institute made excellent progress toward fulfilling or exceeding major targeted outcomes under all of its Objectives by year's end. This provides strong evidence that the Institute's strategic planning has been both sound and effective, and that it is on track to achieve its long-term vision.

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

– Stephen Hawking, September 2012

Achievement Highlights, 2011-12

Advancing Fundamental Research

- ✓ Advanced fundamental research through 326 high calibre papers
- ✓ A recent study by Thomson Reuters showed that in 2010 Canada ranked first in physics citation impact among G8 countries; without Perimeter, Canada would have ranked fourth
- ✓ PI researchers won numerous awards and honours, including:
    - Faculty member Robert Myers won the Canadian Association of Physicists Vogt Medal
    - Faculty member Freddy Cachazo won the Canadian Association of Physicists Herzberg Medal
    - Distinguished Visiting Research Chair Nima Arkani-Hamed won the $3 million Fundamental Physics Prize

Attracting the World's Best

- ✓ Welcomed Xiao-Gang Wen (recruited from MIT) as the BMO Financial Group Isaac Newton Chair and Davide Gaiotto (recruited from the Institute for Advanced Study) as the inaugural Galileo Chair
- ✓ Appointed Bianca Dittrich, Dmitry Abanin, and Kendrick Smith as junior faculty members
- ✓ Jointly recruited Avery Broderick and Roger Melko as associate faculty members with the University of Waterloo
- ✓ Jointly recruited Matthew Johnson as an associate faculty member with York University
- ✓ Hired 15 postdoctoral researchers in 2011-12 and recruited an additional 20 for 2012-13

Training the Scientists of the Future

- ✓ Trained 37 students from 20 countries, including 11 women, through the Perimeter Scholars International (PSI) master's program
- ✓ Trained 35 PhD students

A Global Hub for Scientific Interaction

- ✓ Concluded partnership agreements with the ICTP-South American Institute for Fundamental Research in Sao Paolo, Brazil, and the Institute of Mathematical Sciences in Chennai, India
- ✓ Provided extensive guidance to the African Institute for Mathematical Sciences-Next Einstein Initiative (AIMS-NEI)
- ✓ Held 17 conferences and workshops, attended by 1,013 scientists from around the world
- ✓ Presented 299 scientific talks (271 seminars, 28 colloquia)
- ✓ Hosted 401 visiting scientists
- ✓ Shared the Institute's scientific events virtually: 75,369 visitors from 166 countries accessed the Perimeter Institute Recorded Seminar Archive

Inspiring Through Outreach

- ✓ Reached our one millionth student via PI educational resources
- ✓ Hosted the 10th annual International Summer School for Young Physicists for 39 Canadian and international students
- ✓ Delivered Perimeter content to 955 Aboriginal youth in 61 rural and remote communities in partnership with Actua
- ✓ Held six *GoPhysics!* camps and gave 14 *Physica Phantastica* presentations to over 2,100 students
- ✓ Delivered 85 workshops to more than 3,300 educators throughout Canada and abroad, impacting over 180,000 students
- ✓ Authored the modern physics unit of the grade 12 physics textbook tied to Ontario's curriculum
- ✓ Held festivities for the opening of the Stephen Hawking Centre, attended by over 10,000 on-site visitors and thousands more online and on television
- ✓ Presented 11 sold out Public Lectures, each attended by over 600 people

Creating an Optimal Research Environment

- ✓ Completed the Stephen Hawking Centre at PI on time and on budget, making Perimeter Institute the largest theoretical physics institute in the world
- ✓ Developed a three-tiered scientific computation environment, providing tailored, state-of-the-art computing resources to scientists
- ✓ Launched RECAST, a framework for applying high-energy physics analyses to new models, and Spaces, a tool to facilitate collaborative research

Growing the Public-Private Partnership

- ✓ Finalized federal funding agreement of $50 million, beginning in 2012
- ✓ Finalized provincial funding agreement of $50 million, beginning in 2011
- ✓ Secured $7.8 million in commitments from the private sector including the Krembil Foundation, the John Templeton Foundation, BMO Financial Group, Sun Life Financial, Burgundy Asset Management, Canadian Tire, Scotiabank, CIBC Mellon, Christie Digital, and RBC Foundation, among many others

Perimeter in the News

- ✓ Branded Canada and Perimeter through major media coverage including *The Globe and Mail*, *National Post*, *Toronto Star*, *Macleans*, *CTV*, *CBC*, *NBC*, *Wall Street Journal*, *Australian Herald*, *Nature*, *Science*, *National Geographic News*, *Der Spiegel*, and *The Economist*, among others.

Statement of Objectives for 2011-12

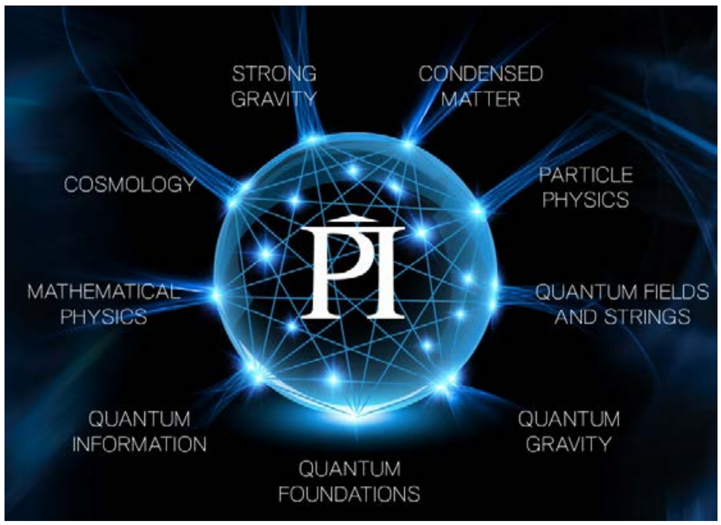
Objective 1:	To deliver world-class research discoveries
Objective 2:	To become the research home of a critical mass of the world's leading theoretical physicists
Objective 3:	To create the world's best environment and infrastructure for theoretical physics research, training, and outreach
Objective 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 and math 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

Objective 1: To deliver world-class research discoveries

Summary of Achievements

- Advanced fundamental research through 326 high calibre papers[2]
- Since inception, PI researchers have produced 2,129 papers appearing in over 50 journals, which have attracted 48,567 citations to date, attesting to the importance and long-term impact of PI research[3]

Highlights

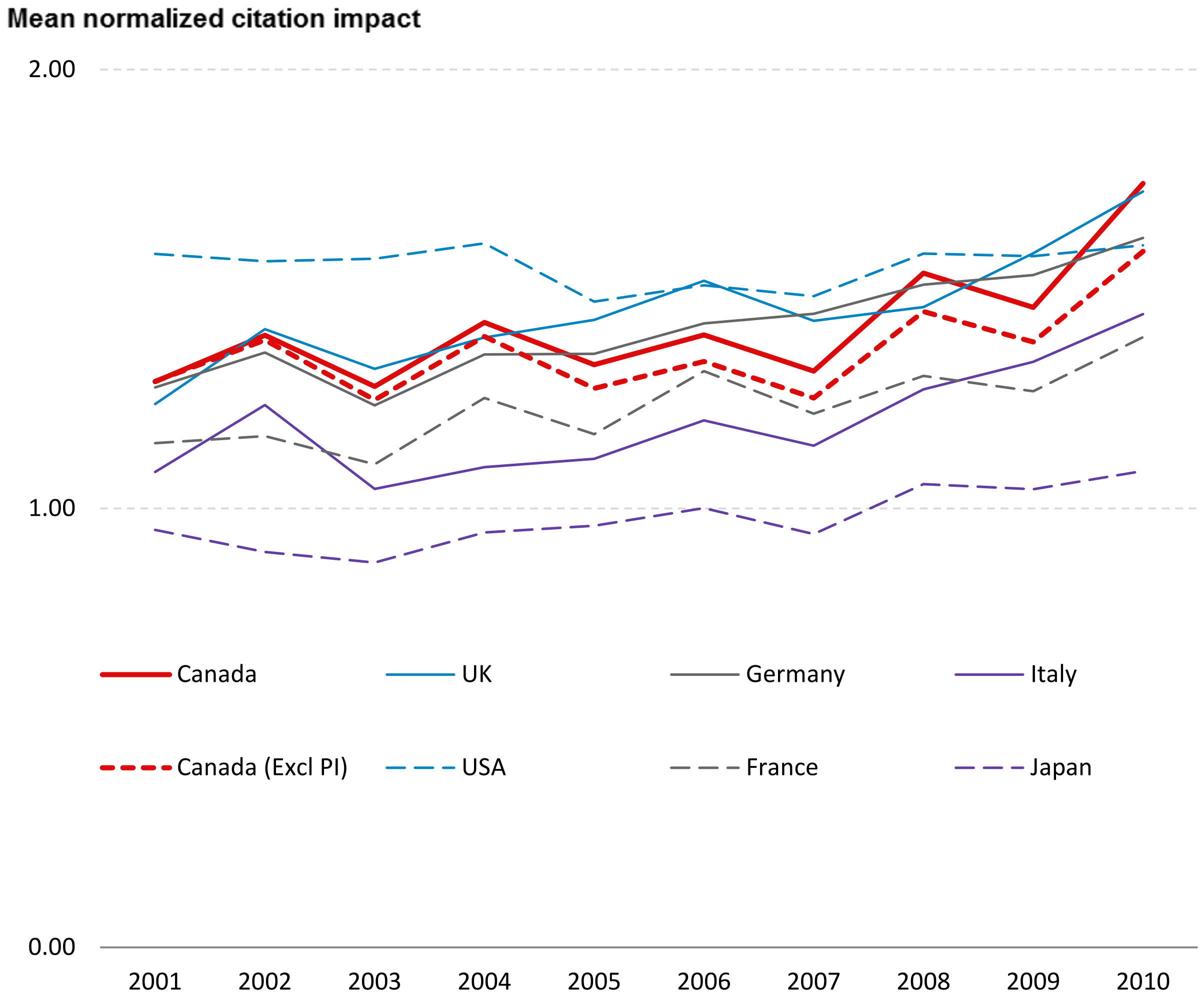


Thomson Reuters Study

Perimeter Institute's overriding goal is to foster breakthrough research. To that end, it prioritizes foundational research across a strategically chosen set of research fields and promotes a dynamic interchange of ideas among them in order to accelerate discovery. This approach is paying off – for theoretical physics and for Canada. A recent study conducted by Thomson Reuters indicates that Perimeter is doing very high-quality, high-impact research and making a major contribution to increasing Canada's standing in the global scientific community.[4]

[2] During the one-year period August 1, 2011 to July 31, 2012. Each publication has been counted only once, regardless of how many Perimeter Institute researchers collaborated on it.
[3] According to Google Scholar and Spires databases, as of August 1, 2012. Each publication is counted only once, regardless of how many PI researchers were co-authors.
[4] The report analyzed bibliometric data from *Web of Science* databases, part of the Thomson Reuters *Web of Knowledge*, which covers 11,500 of the highest impact journals worldwide, including Open Access journals and 110,000 conference proceedings.

The data indicate that the citation impact of Perimeter's published research is well above the Canadian average and has increased substantially in recent years. The graph below indicates that since Perimeter's inception, Canada's physics citation impact has risen dramatically relative to other countries, with Perimeter making a significant and growing contribution. In 2010, among G8 countries, Canada ranked first in physics citation impact; without Perimeter, Canada would have ranked fourth.



Source: Thomson Reuters (*Evidence)*

Research

Scientists at Perimeter pursue creative, interdisciplinary approaches to some of the most challenging problems in fundamental physics. This year, many have produced results of international impact and importance. Some notable examples are outlined below.

"A Bayesian approach to compatibility, improvement, and pooling of quantum states," M.S. Leifer (University College London) and R.W. Spekkens (Perimeter Institute), [arxiv: 1110.1085].

Robert Spekkens and Matt Leifer have been advancing the research program of how to formulate quantum theory as a theory of Bayesian inference. This work seeks to resolve the conceptual difficulties of quantum theory by interpreting quantum states not as states of reality, as in most other interpretations, but as states of incomplete knowledge, expressing the degrees of belief of an agent. A theory of Bayesian inference specifies how an agent ought to modify her degrees of belief in light of new information (Bayesian conditioning) and how beliefs about different systems are connected (belief propagation). If the quantum state is regarded as a representation of knowledge, then two agents can assign different states to the same quantum and this raises two questions: when are such state assignments compatible? And how should the state assignments of different agents be reconciled? In 2011, Spekkens and Leifer wrote an article providing answers to these questions using a Bayesian methodology, achieving a degree of deductive rigour significantly beyond that of previous work in the area. Towards this end, they developed quantum analogues of the notions of conditional independence and sufficient statistics. These concepts are also proving crucial for understanding how to generalize our formulation of quantum theory to general instances of Bayesian conditioning and belief propagation.

"Prisoners of their own device: Trojan attacks on device-independent quantum cryptography," Jonathan Barrett (University of London), Roger Colbeck (Perimeter Institute), and Adrian Kent (Perimeter Institute/University of Cambridge), [arXiv:1201.4407].

Quantum cryptography, on paper, has the potential to offer ultimate security, leading to secret codes whose security relies only on the laws of physics. Quantum measurements inherently disturb the system being measured, meaning the users of a quantum cryptographic system could rapidly detect and shut down any attempt at eavesdropping. However, real-world implementations of quantum cryptography will always depart from the idealized systems designed by theorists, which can potentially lead to security holes an eavesdropper can exploit.

Theorists have responded to the challenge by pointing out even stronger security properties of quantum mechanics: There are quantum cryptography systems that may well be secure no matter how poorly designed the implementation. Such 'device-independent' quantum cryptography systems should remain secure even if the people communicating are using an apparatus that was built by the eavesdropper! However, Barrett, Colbeck, and Kent have now shown that there are definite limits to that security, showing that if the apparatus is used more than once, the eavesdropper can design it to smuggle out critical information about old messages by disguising it as legitimate communications by the system.

This means that while device-independent quantum cryptography should help protect against careless device design, it is probably not strong enough to guard against machines that have been completely subverted by the eavesdropper. This result was highlighted on MIT's Technology Review website.

"Colored Tensor Models – a Review," Razvan Gurau (Perimeter Institute) and James P. Ryan (Albert Einstein Institute), *SIGMA* 8 (2012), 020, [arXiv:1109.4812].

This article reviews the state of the art for a research program pioneered in the past few years by PI Senior Postdoctoral Fellow Razvan Gurau. Gurau's motivation is one of the most basic and salient questions in quantum gravity: What is the fundamental nature of spacetime? Several alternative pictures have been proposed over the years. Quantum mechanics suggests that at some level space could be granular – that is, made of discrete pieces that cannot be broken apart. Field theory, meanwhile, teaches us that at some level it should fluctuate randomly. Can these two ideas be combined into a coherent framework describing randomly fluctuating discretized spaces? To do so would be a major step toward unifying quantum field theory and general relativity into a theory of quantum gravity, often called the Holy Grail of modern physics.

A full theory of quantum gravity has eluded physicists for 80 years, but 40 years ago, they began to make progress on a simplified version of the problem. A highly successful theory of random two-dimensional surfaces has been extensively developed. In addition to providing a toy model of a theory of quantum gravity in two dimensions, this theory found application in a wide array of other topics ranging from the theory of strong interactions (describing the forces binding nuclei) to the study of crystal growth.

Of course, the spacetime in which we live is four-dimensional (three spatial directions plus time). Since the 1990s, many attempts were made to build an analogous theory of random four-dimensional spaces, but all proved fruitless. Starting in 2009, Gurau constructed a new mathematical framework which generalized matrix models, the underlying structure in the successful two-dimensional theory, to higher dimensions. In a series of papers published in 2010, Gurau developed a so-called '1/N expansion' for these new models which proved that they provided a well-defined, analytically controlled framework for the study of random spaces in higher dimensions. In other words, they showed the path from two-dimensional models to four-dimensional ones.

The work quickly attracted widespread attention and has catalyzed major developments in the past year and a half. Beyond quantum gravity, this breakthrough may lead to a spectrum of applications ranging from conformal field theory to statistical physics and condensed matter physics. For his seminal contributions in initiating this new research program, Gurau has been awarded the 2012 Hermann Weyl Prize.

“Quantum Criticality with the Multi-scale Entanglement Renormalization Ansatz,” Glen Evenbly (Caltech) and Guifre Vidal (Perimeter Institute), [arXiv:1109.5334]. Note: This paper will appear as a chapter in *Numerical Methods for Strongly Correlated Systems*, edited by Adolfo Avella and Ferdinando Mancini (Springer).

This work concerns the study of quantum critical systems, which are of high interest in condensed matter, using a tensor network state approach, which originated in quantum information. In the absence of better tools, a traditional approach to understanding critical quantum systems has consisted of making an educated guess (based mainly on symmetry arguments) of which field theory describes the low energy limit of the system. In other words, faced with a very difficult problem, instead of solving it, it was simply assumed that it is equivalent to something else for which there are good tools.

This paper (to appear as a book chapter) describes recent progress on the multi-scale entanglement renormalization ansatz (MERA), which can be used to deterministically obtain, instead of guessing, the (conformal) field theory associated with any given critical quantum spin chain. This work provides a clear example of how concepts and ideas from quantum information can contribute to progress in condensed matter. The MERA is based on understanding the universal pattern of quantum entanglement present in the ground state of quantum many-body systems at criticality. This is one of the most important and clear-cut condensed matter results obtained with tensor networks to date. The researchers are now investigating how to export the success of MERA to higher dimensional lattice models. PI is an ideal place for further progress, thanks to its multidisciplinary environment.

“Entropy of non-extremal black holes from loop gravity,” Eugenio Bianchi (Perimeter Institute), [arXiv:1204.5122].

One of the most remarkable discoveries in fundamental physics was the realization that black holes carry entropy. This property was originally suggested in 1973 by Jacob Bekenstein, but in 1975, Stephen Hawking (now a Perimeter Distinguished Visiting Research Chair) was able to present a precise formula for the entropy of a black hole. The now celebrated Bekenstein-Hawking (BH) formula is seen as profound because it draws an unexpected connection between spacetime geometry, thermodynamics, quantum theory, and gravity. Much of the interest in this result has long been sparked by the possibility that it may provide a window into the nature of quantum gravity. Hawking’s derivation of the BH formula is somewhat indirect and uses various approximations; thus, providing a first principles derivation of this result in terms of a fundamental theory of quantum gravity has been a major open problem since Hawking’s original work. The paper above by Postdoctoral Researcher Eugenio Bianchi provides precisely such a derivation of the BH entropy of a general black hole.

In the past, various successes had been achieved in describing the entropy of very special classes of black holes, known as extremal black holes, using the fundamental degrees of freedom in a theory of quantum gravity. Bianchi’s paper presents for the first time a derivation where such a fundamental explanation is achieved for generic black holes. His calculation relies on an approach called ‘loop quantum gravity’, in which the smooth geometry of space and time emerges from a description that is discrete at a fundamental level. Previous work in loop quantum gravity by Ashtekar and collaborators only obtained the correct entropy by precisely tuning the value of a parameter in the theory called the Immirzi parameter. Bianchi's calculation avoids this issue and gets the correct exact value for the BH entropy for all values of that parameter. This work can also be applied in new variations of loop quantum gravity (related to recent work by Perimeter's Laurent Freidel and others) and their description of black holes. Bianchi's result can be seen as evidence that the ongoing research on loop quantum gravity, and particularly on the recently developed spin foam models, is on the right track.

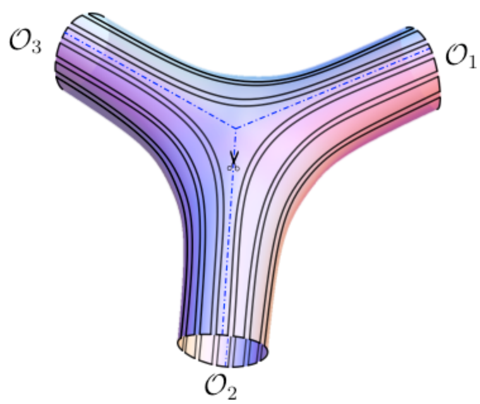
"Statistical Tests of Noise and Harmony in Dark Matter Modulation Signals," Josef Pradler (Perimeter Institute), Spencer Chang (University of Oregon), and Itay Yavin (Perimeter Institute), *Phys. Rev. D* 85, 063505 (2012), [arxiv:1111.4222].

The DAMA collaboration has claimed evidence for the direct detection of dark matter by observing annual modulations in the energy deposited in their NaI crystals (see, for example, arXiv:1002.1028). This has generated considerable controversy in the community, especially since other experiments have not seen these modulations (although, for various reasons, no other experiment has so far directly reproduced the DAMA setup). Over the years, several alternative explanations have been suggested and, most recently, the possible role of the muon flux from the atmosphere has been emphasized. Due to the changes in the atmospheric density over the course of a year, the muon flux modulates. Thus, it may account for the annual modulations observed by the DAMA experiment since these atmospheric muons reach deep underground where the experiment is located. In arxiv:1111.4222, Associate Faculty member Itay Yavin, together with Pradler and Chang, have shown that the temporal modulations associated with the muon flux are incompatible at high statistical significance with the modulations observed by DAMA. In doing so, they have developed several powerful statistical techniques including a generalization of the Lomb-Scargle periodogram to include information about the phase of the modulations. In addition, the researchers proposed new signals associated with the possible recoil of dark matter against matter that may be helpful in future searches for dark matter in the lab. The signal reported by the DAMA collaboration remains a mystery and whether it is indeed due to the recoil of dark matter against the crystals is still not known. The importance of this work is in excluding one plausible alternative explanation for the origin of this signal. In doing so, it is hoped that it will bring us closer to the truth behind the DAMA signal.

"Tailoring Three-Point Functions and Integrability," Jorge Escobedo (Perimeter Institute), Nikolay Gromov (King's College London), Amit Sever (Perimeter Institute), and Pedro Vieira (Perimeter Institute), *JHEP* 1109 (2011) 028, [arXiv:1012.2475].

For over 15 years, string theorists have been studying a remarkable equivalence stating that certain particle theories – of the sort used to describe collisions at the Large Hadron Collider – may be equivalently described in terms of a theory of quantum gravity where the fundamental particles are small vibrating loops known as strings. These equivalences are often called 'holographic' because the string theory lives in a spacetime with more dimensions than the particle theory. Holography has thus radically revised our understanding of both of these theories. Fully understanding how these loops emerge, and their dynamics, is an important problem which would greatly improve our understanding of both particle theories and quantum gravity.

The dynamics of strings can be described by two main processes: *propagation,* describing how the strings move in space and time, and *interactions,* in which a single string can split into two smaller strings or two small strings can merge into a bigger one. The propagation part of the dynamics is considerably simpler than the interaction part and indeed powerful techniques (known as *integrability*) have been employed in recent years to efficiently compute this process. This paper takes the first steps towards understanding the second, very important, process of string interactions. Perimeter researchers Jorge Escobedo, Amit Sever, and Pedro Vieira, together with Nikolay Gromov from King's College London, explain how the interaction part of the string dynamics can be addressed using holography and integrability. Their description of these interactions becomes a 'tailoring'-like process of cutting and sewing the strings, as depicted in the figure below:



In a series of follow-up papers, these authors and others have continued to develop this line of research to account for more quantum effects, as well as simplifying previous results. It is now believed that the full description of string dynamics can be realized in the foreseeable future.

"The Cosmological Impact of Luminous TeV Blazars I: Implications of Plasma Instabilities for the Intergalactic Magnetic Field and Extragalactic Gamma-Ray Background," Avery E. Broderick (Perimeter Institute/University of Waterloo), Philip Chang (CITA/University of Wisconsin-Milwaukee), and Christoph Pfrommer (CITA/Heidelberg Institute for Theoretical Studies), *ApJ*, 752, 22 (2012); "The Cosmological Impact of Luminous TeV Blazars II: Rewriting the Thermal History of the Intergalactic Medium," Avery E. Broderick, Philip Chang, and Christoph Pfrommer, *ApJ*, 752, 23 (2012); "The Cosmological Impact of Luminous TeV Blazars III: Implications for Galaxy Clusters and the Formation of Dwarf Galaxies," Avery E. Broderick, Philip Chang, and Christoph Pfrommer, *ApJ*, 752, 24 (2012); "The Lyman-alpha forest in a blazar-heated Universe," Ewald Puchwein (Heidelberg Institute for Theoretical Studies), Christoph Pfrommer, Volker Springel (Heidelberg Institute for Theoretical Studies), Avery E. Broderick, and Philip Chang, *MNRAS*, 423, 149 (2012).

Associate Faculty member Avery Broderick and collaborators have proposed a novel feedback mechanism by which supermassive black holes impact the intergalactic medium on cosmological scales and described a number of robust observational consequences, many of which have already been detected. This feedback is due to the extremely high energy gamma-ray emission from a handful of accreting supermassive black holes, dubbed TeV blazars. Ultimately, the energy emitted into these gamma rays ends up heating the enormous voids between clusters of galaxies – which, despite their low density, still contain the overwhelming majority of the mass of the universe – and raising their temperatures by as much as two to three orders of magnitude. The hotter than previously expected gas directly impacts the statistics of absorption lines in the spectra of high-redshift quasar (high-redshift Lyman-alpha lines), the formation and evolution of galaxy clusters and groups, and the formation of dwarf galaxies. In addition, the existence of a new potential channel for the original gamma ray luminosity from TeV blazars has had dramatic consequences for the statistics of the high-redshift TeV blazar population, allowing many more such objects than had previously been thought and more naturally unifying these with other populations of accreting black holes. The process by which the gamma-ray emission heats the intergalactic medium involves a wide array of physical mechanisms, including cosmological-scale plasma instabilities, observational statistics of accreting black holes as seen at TeV and GeV energies, radiative transfer of both high energy gamma rays and much lower energy ultraviolet photons, the various heating and cooling processes within the intergalactic medium, and the growth of gravitational instabilities. This year, Broderick and collaborators made substantial progress on each of these topics, resulting in the four publications listed above, which have already attracted 42 citations. Future work must ascertain the non-linear growth of the aforementioned plasma instabilities and refine the rough predictions for the consequences of the subsequent heating we have already made. However, if such plasma instabilities are indeed present, they necessitate a complete rewriting of the thermal history of the recent universe (redshifts less than about 4).

"Probing the inflaton: Small-scale power spectrum constraints from measurements of the CMB energy spectrum," Jens Chluba (CITA), Adrienne Erickcek (Perimeter Institute/CITA), and Ido Ben-Dayan (Perimeter Institute/CITA), *Astrophysical Journal* 758, 76 (2012) [arXiv:1203.2681].

One of the main goals of cosmology is to determine what the universe was like during the first instants after the Big Bang, and why. The universe today is extremely lumpy and non-uniform (filled with a diverse array of galaxies, stars, and planets, separated by vast empty spaces), but during the first instants after the Big Bang it was very different – a nearly uniform soup of particles, with only tiny fluctuations in density from one point in space to the next. Measurements of these primordial density perturbations give us our most detailed and precise clues about the infant universe. To date, cosmologists have only been able to measure the long-wavelength fluctuations, but Postdoctoral Researcher Adrienne Erickcek and her collaborators have presented a new technique to make a much more sensitive measurement of the short-wavelength fluctuations as well, via the imprint they leave in the low-frequency spectrum of a cosmic bath of radiation called the cosmic microwave background. They have shown that, by applying their technique to data already obtained by the COBE satellite mission, they are already able to constrain the short-wavelength primordial density perturbations 1,000 times better than a previous technique (based on the non-observation of primordial black holes) and they point out that a proposed experiment called PIXIE would improve the constraint by yet another factor of 1,000.

Honours, Awards, and Major Grants

Many Perimeter researchers have received national and international recognition in 2011-12. Notable among these are the following:

- Director Neil Turok has been selected to deliver the 2012 Massey Lectures, which will be presented in five cities across Canada, aired nationally on CBC Radio, and published as a book

- Faculty member Robert Myers won the Canadian Association of Physicists 2012 Vogt Medal for his important contributions to subatomic physics

- Faculty member Freddy Cachazo won the Canadian Association of Physicists 2012 Herzberg Medal, recognizing outstanding achievements by a physicist early in their career

- Distinguished Visiting Research Chair Nima Arkani-Hamed was named one of the nine inaugural winners of the Fundamental Physics Prize, recognizing his "original approaches to outstanding problems in particle physics, including the proposal of large extra dimensions, new theories for the Higgs boson, novel realizations of supersymmetry, theories for dark matter, and the exploration of mathematical structures in gauge theory scattering amplitudes"

- The 2012 Best Paper Prize, given by the Institute of Physics (IOP) and the Editorial Board of *Journal of Physics A* was awarded to "Y-system for scattering amplitudes" by Faculty member Pedro Vieira, Senior Postdoctoral Fellow Amit Sever, et al.

- Director Neil Turok and Faculty member Lee Smolin were awarded $2 million by the John Templeton Foundation to create the Templeton Frontiers Program at Perimeter Institute to catalyze path-breaking research in quantum foundations and information, foundational cosmology, and the emergence of spacetime

- Faculty member Pedro Vieira was awarded an Early Researcher Award from the Ministry of Research and Innovation of Ontario

- Associate Faculty member Adrian Kent was awarded a grant from the John Templeton Foundation of GBP 178,000, 2011-13

- Associate Faculty member Raymond Laflamme was named a Fellow of the American Physical Society for his visionary leadership in the field of quantum information science

- Associate Faculty member Raymond Laflamme was named a Fellow of the American Association for the Advancement of Science

- Senior Postdoctoral Fellow Razvan Gurau was awarded the 2012 Hermann Weyl Prize for the discovery and development of the theory of coloured random tensors

- Postdoctoral Researcher Eugenio Bianchi was awarded a Banting Postdoctoral Fellowship to be held at Perimeter

- Director Neil Turok was named to the International Advisory Committee of the Higgs Centre for Theoretical Physics at the University of Edinburgh

- Associate Faculty member Michele Mosca and co-applicants were awarded an NSERC CREATE grant of $1.65 million, 2012-18

- Associate Faculty member Matt Johnson and co-applicants were awarded a New Frontiers in Astronomy and Cosmology grant of $270,000 over two years

- Senior Research Affiliate John Moffat was awarded a John Templeton Foundation grant of $222,000 over three years to support his research into promising alternative models in physics

- Ten Perimeter researchers were awarded NSERC Discovery Grants totalling $1,668,000 (over three- to five-year terms), including one Discovery Accelerator Supplement of $120,000, as follows:
    - Faculty member Guifre Vidal: $305,000 over five years
    - Faculty member Bianca Dittrich: $210,000 over five years
    - Faculty member Lucien Hardy: $165,000 over five years
    - Senior Researcher Rafael Sorkin: $165,000 over five years
    - Faculty member Latham Boyle: $150,000 over five years, with an Early Career Supplement
    - Faculty member Pedro Vieira: $126,000 over three years
    - Associate Faculty member Avery Broderick: $125,000 over five years, with an Early Career Supplement
    - Research Technologies Group Lead Erik Schnetter: $125,000 over five years
    - Associate Faculty member Itay Yavin: $90,000 over three years, with an Early Career Supplement
    - Faculty member Philip Schuster: $87,000 over three years, with an Early Career Supplement and a $120,000 Discovery Accelerator Supplement

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

Summary of Achievements

- Welcomed Xiao-Gang Wen, one of the world's top condensed matter theorists, as the BMO Financial Group Isaac Newton Chair in Theoretical Physics at Perimeter Institute
- Welcomed Davide Gaiotto as the inaugural Galileo Chair at Perimeter Institute
- Appointed Bianca Dittrich as a junior Faculty member, bringing the full-time Faculty to 18
- Appointed Avery Broderick as an Associate Faculty member working jointly with the University of Waterloo, bringing the part-time Associate Faculty to 12
- Recruited Dmitry Abanin and Kendrick Smith as junior Faculty members to begin in 2012, as well as Roger Melko and Matthew Johnson as Associate Faculty members jointly appointed with the University of Waterloo and York University, respectively

Highlights

The Perimeter Research Chairs

The Perimeter Research Chairs program was designed to attract stellar, senior researchers to Perimeter and to Canada. Perimeter plans to create five such chairs in total, named for legendary scientists whose insights helped define modern physics: Neils Bohr, Albert Einstein, Leonhard Euler, James Clerk Maxwell, and Isaac Newton. In May 2012, the Institute welcomed world-leading condensed matter theorist Xiao-Gang Wen as the BMO Financial Group Isaac Newton Chair at Perimeter Institute. Together with recent hires Guifre Vidal, Dmitry Abanin, and Sung-Sik Lee, Dr. Wen forms the core of the Institute's fast-growing research team in condensed matter.

Also in 2011-12, Perimeter launched an international search to identify potential candidates for the remaining Chairs. Since the Chairs are to be recruited from the very top tier of scientists worldwide, their recruitment cannot be precisely timetabled; however, an outstanding candidate for the Euler Chair has been identified, the Institute is in serious discussions with this candidate, and an endowment to support their hiring has been pledged (see Objective 10).

Xiao-Gang Wen joined Perimeter's faculty in May 2012. He received his PhD from Princeton University in 1987, under the supervision of Edward Witten. Widely recognized as one of the world's leaders in condensed matter theory, he pioneered the new paradigm of quantum topological order, used to describe phenomena from superconductivity to fractionally charged particles, and has invented many new mathematical formalisms. He authored the textbook *Quantum Field Theory of Many-body Systems:*

From the Origin of Sound to an Origin of Light and Electrons. Wen was previously a Distinguished Moore Scholar at Caltech and the Cecil and Ida Green Professor of Physics at MIT, as well as one of Perimeter's own Distinguished Visiting Research Chairs. He is also a fellow of the American Physical Society.

Galileo Chair – New Initiative

In addition to the five Perimeter Research Chairs for senior scientists, Perimeter created the Galileo Chair at Perimeter Institute, a five-year appointment designed to attract an exceptional early career scientist. In May 2012, Davide Gaiotto, widely regarded as the leading young quantum field theorist worldwide, arrived as the first holder of the Galileo Chair. He chose to come to Perimeter in the face of very strong competition from Stanford, Rutgers, and Stony Brook University.

Davide Gaiotto received his PhD from Princeton University in 2004 under the supervision of Leonardo Rastelli, was a postdoctoral fellow at Harvard from 2004 to 2007, and was a long-term Member at the Institute for Advanced Study in Princeton from 2007 to 2011. Gaiotto works in the area of strongly coupled quantum fields and has achieved several important conceptual advances, with potentially revolutionary implications. He was awarded the 2011 Gribov Medal of the European Physical Society.

Faculty Recruitment

In 2011-12, in addition to Xiao-Gang Wen and Davide Gaiotto, Perimeter welcomed Bianca Dittrich to its growing faculty, which now comprises eighteen full-time faculty members.

In line with targeted outcomes, the Institute also recruited two outstanding junior faculty members, Dmitry Abanin and Kendrick Smith. Dr. Smith has been granted a one-year leave of absence from his start date to participate in the start-up phase of the major Hyper-Suprime Cam (HSC) project on the Hawaii-based Subaru telescope, after which he will bring full data rights to Perimeter. He will also lead Perimeter's participation in the Large Synaptic Survey Telescope (LSST), which will follow the HSC and lead to unprecedented tests of both dark energy and other signals of primordial physics.

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

New Faculty Recruited in 2011-12:

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

Kendrick Smith will join Perimeter from Princeton University, where he has been the Lyman P. Spitzer Postdoctoral Fellow since 2009. Prior to this, he was the PPARC Postdoctoral Fellow at the University of Cambridge from 2007 to 2009. Smith earned his PhD at the University of Chicago under the supervision of Wayne Hu. He is a cosmologist whose work focuses on physics of the early universe, statistical methods, large-scale computing, and data analysis. His research has included the first detection of gravitational lensing in the cosmic microwave background and the first implementation of statistically optimal estimators for primordial non-Gaussianity in the CMB. He is currently a member of the WMAP team that was awarded the 2012 Gruber Cosmology Prize, as well as the QUIET and Planck experiments.

Associate Faculty Recruitment

The Associate Faculty program enables Perimeter Institute to partner with Canadian universities in order to attract and retain top scientific talent, thereby helping to build Canada's stature in fundamental physics. In the fall of 2011, Avery Broderick joined Perimeter in a joint appointment with the University of Waterloo, giving the Institute 12 Associate Faculty members.[5] In line with the year's targeted objectives, Perimeter also recruited Matthew Johnson and Roger Melko, who will be jointly appointed with York University and the University of Waterloo, respectively.

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

[5] Note that Associate Faculty are appointed for fixed terms ranging from five to seven years. Also in the fall of 2011, three Associate Faculty members completed their terms – namely, Richard Cleve, Ashwin Nayak, and Thomas Thiemann.

New Associate Faculty Recruited in 2011-12:

Matthew Johnson will be jointly appointed with York University, beginning in August 2012. He completed his PhD at the University of California, Santa Cruz, in 2007 and was a Moore Postdoctoral Scholar at Caltech from 2007 to 2010, when he joined Perimeter as a Postdoctoral Researcher. Johnson's research seeks to understand the fundamental laws of nature through their impact on cosmology. He designs data analysis algorithms to confront fundamental theory with observations of the Cosmic Microwave Background (CMB) radiation. Johnson's work crosses a number of disciplines, including cosmology, field theory, string theory, numerical relativity, and gravitation.

Roger Melko will join Perimeter in fall 2012 in a joint appointment with the University of Waterloo, where he has been an Associate Professor in the Department of Physics and Astronomy since 2007. He completed his PhD at the University of California, Santa Barbara, in 2005, after which he was a Wigner Fellow at Oak Ridge National Laboratory (2005-07). Melko is a condensed matter theorist whose research involves strongly-correlated many-body systems. He emphasizes computational methods, in particular the development of state-of-the-art algorithms for the study of strongly-interacting systems. Melko received an Early Researcher Award in 2010.

Objective 3: To create the world's best environment and infrastructure for theoretical physics research, training, and outreach

Summary of Achievements

- Completed final phases of a major expansion project, the Stephen Hawking Centre at Perimeter Institute
- Upgraded several key IT systems, including the Institute's various web platforms and contact relationship management (CRM) system, and introduced a new information wall
- Developed a three-tiered scientific computation environment to meet researchers' increasing computational needs
- Launched two new scientific resources: RECAST, a framework (in beta) for applying high-energy physics analyses to new models, and Spaces, a tool to facilitate collaborative research (see Objective 7)

Highlights

The Stephen Hawking Centre at Perimeter Institute

By September 2011, in line with targeted objectives, the Stephen Hawking Centre (SHC) expansion was completed on time and on budget, with all scientists, students, and administrative staff housed under one roof. Perimeter is now the largest independent theoretical physics institute in the world, able to accommodate up to 250 scientists and research trainees. Designed by Teeple Architects, the SHC has received several accolades, including a 2012 Design Excellence Award from the Ontario Association of Architects.

IT Upgrades

In 2011-12, Perimeter continued to upgrade its IT systems to provide state-of-the-art research tools and to optimize administrative efficiency, in line with a comprehensive, multi-year strategy. A major website project was undertaken and most phases were completed by July 31, 2012. Although the launch of the new Perimeter website was initially scheduled for summer 2012, this has been rescheduled to late fall due to an expansion in the scope of the project to include hosting of Perimeter's intranet and extranet portals, as well as an online donation management system.

Some of the other projects undertaken in 2011-12 to optimize the Institute for all research, training, and outreach purposes include the following:

- Delivered a new video feature wall to deliver targeted, multimedia messages to residents, visitors, and the general public; in addition to delivering timely information, the wall can display high-resolution scientific visualizations as a tool for both research and outreach
- Installed 13 interactive digital signs throughout the building to deliver event and way-finding information, which will be launched with the new website
- Implemented a new contact relationship management (CRM) system, consolidating several pre-existing systems into a single tool that can be used across departments, increasing efficiency

Scientific Computing

Scientific computing is increasingly important to theoretical physics. Recognizing the need for dedicated IT services to support research, Perimeter's Research Technology Group has implemented a flexible and efficient three-tiered scientific computation environment to meet researchers' computational requirements, as follows:

1. Workstation class personal computers support complex multi-threaded/multitasking applications and complex graphics to assist in analyzing large and complicated data sets.
2. A shared scientific computing environment provides immediate access to scalable server instances to perform advanced analyses. This environment provides generic research server resources and universal computing environments comprising servers with an array of scientific software and collaboration tools.
3. The High Performance Computing Cluster (HPCC) enables Perimeter scientists to execute complex analyses and simulations in a timely manner. HPCC access, combined with the expertise provided by Perimeter's Research Technology Group in numerical and computational algorithms, has recently been a key factor in the recruitment of several researchers.

Scientific Software

To maximize research productivity and collaboration, Perimeter launched two new scientific resources in 2011-12, both of which will enhance not just Perimeter's research community, but the physics community at large.

- High-energy physics experiments are very costly and can take years to set up and run, and the experiments are often sensitive to a broader class of models than they were originally designed to test. To take advantage of these characteristics, Associate Faculty member Itay Yavin and Kyle Cranmer (NYU, ATLAS) worked with Perimeter's IT group to develop **RECAST**, a new computational framework for particle physics research (http://recast.perimeterinstitute.ca/). RECAST enables researchers to efficiently make use of *existing* analyses from high-energy physics experiments to test alternative models. Over the last year, a functional beta version was launched and has been used by physicists around the world. A recent white paper from the

Study Group for Data Preservation and Long Term Analysis in High Energy Physics highlighted RECAST as a notable example of shared research models.[6]

- In 2011-12, **Spaces** was developed to facilitate collaborative projects between researchers at Perimeter and other institutes. For each new project, Spaces provides researchers with a standardized set of tools – including mailing lists, repositories, wikis, etc. – to improve the efficiency of collaborative research, while ensuring the safety of researchers' data and long-term archival storage.

Expansion of Library Collection

In 2011-12, Perimeter continued to expand its resource collections and enhance access to journals and other electronic content, as part of a comprehensive strategy to become a well-resourced centre for resident and visiting researchers. The library added 331 new texts, bringing the total to 5,083 in the print collection (5,405 items in all formats). This exceeds the targeted objective of 5,000 volumes by 2014. Perimeter also completed an extensive user needs assessment, involving focus groups spanning the Institute's entire research spectrum, and started a multi-year collection analysis.

[6] "Status Report of the DPHEP Study Group: Towards a Global Effort for Sustainable Data Preservation in High Energy Physics," Study Group for Data Preservation and Long Term Analysis in High Energy Physics. http://arxiv.org/abs/1205.4667

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

Summary of Achievements

- Hired 15 postdoctoral researchers in 2011-12 and recruited an additional 20 for 2012-13
- Trained 37 students from 20 countries, including 11 women, through the Perimeter Scholars International (PSI) master's training program
- Trained 35 PhD students and one MSc student (in addition to those in the PSI program)
- Attracted 10 Visiting Graduate Fellows over the course of the year
- Provided research training to eight undergraduate students

Highlights

Postdoctoral Researchers

Fifteen postdoctoral researchers joined Perimeter in 2011-12 and an additional 20 have been recruited for 2012-13, meeting the Institute's goal of maintaining the number of postdoctoral researchers at an approximately steady state.[7] The number of incoming postdoctoral researchers is up slightly from previous years, reflecting a strategic increase to offset the increased number of postdoctoral researchers finishing their terms; the appointment of three new fellows through the Templeton Frontiers Program[8] (see Objective 10); and increased flexibility in the Institute's recruitment approach, which has resulted in collaborative postdoctoral hires with other world-class institutes such as the University of Oxford, Institute for Advanced Study (IAS), University of Waterloo, and Canadian Institute for Theoretical Astrophysics (CITA).[9]

Perimeter remains a top destination for the world's brightest early-career scientists; in fact, the applicant pool for 2012-13 was the largest in the Institute's history at 662, up nearly 40 percent from just three years ago.

Perimeter's postdocs benefit from an exceptional research training environment, where they are encouraged to pursue novel, ambitious lines of research. In order to broaden their skill set, they are encouraged to work with experimentalists and observational scientists. To this end, in 2011-12, Perimeter instituted its "Get Out" (GO) Program, giving early career particle physicists new

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[7] Perimeter had 38 postdoctoral researchers in residence as of July 31, 2012.
[8] Namely Kurt Hinterbichler in cosmology, Ryszard Kostecki in quantum foundations, and Flavio Mercati in quantum gravity.
[9] Tim Johannsen will split his time between Perimeter, CITA, and UW; Matthew Bullimore will spend one year each at Oxford, Perimeter, and IAS; and Song He will spend two years at Perimeter and one year at IAS.

opportunities to work with experimentalists at centres such as CERN, FermiLab, Jefferson Lab, TRIUMF, SNOLAB, and SLAC (see Objective 7).

The value of Perimeter's training is evidenced by the success of its postdocs in obtaining coveted academic positions. In 2011-12, despite an extremely competitive market for academic positions worldwide, four departing postdoctoral researchers obtained tenure-track faculty positions: Giulio Chiribella (Tsinghua University), Thomas Giblin (Kenyon College), Sarah Shandera (Pennsylvania State University), and David Skinner (University of Cambridge). The majority of Perimeter's other departing postdoctoral researchers obtained continuing fellowships at international institutions (including the Institute for Quantum Computing, University of Oxford, and ETH Zurich), and positions in industry.

Perimeter Scholars International (PSI)

- In 2011-12, the PSI program trained 37 students, including 11 women, from 20 countries

This master's level program attracts highly talented university graduates from around the world to Perimeter and brings them to the cutting edge of theoretical physics in just one academic year. Admission is highly competitive: for 2012-13, 30 students from 15 countries, including 11 women, have been accepted from a field of over 300 applicants from 60 countries.[10] As a result, the quality of students is extremely high; many of the entering students hold competitive scholarships, including three NSERC scholarships, a FQRNT scholarship, and a Rhodes Scholarship finalist.

PSI's innovative curriculum features modular three-week courses taught by Perimeter faculty and other top lecturers from around the world,[11] supported by postdoctoral level Tutors and graduate teaching assistants. It continues to strengthen the Institute's ties with its regional partners – including the University of Waterloo, McMaster University, and the University of Guelph, whose faculty present research talks, assist as lecturers, and act as both research supervisors and essay examiners. PSI graduates receive their master's degree from the University of Waterloo upon completion of the program. In addition, in 2011-12, Perimeter opened up some PSI courses to Waterloo PhD students.

PSI brings graduates with high scientific potential to Perimeter and selects the best among them for continued doctoral training. Fourteen of the 2011-12 graduates are pursuing their PhDs in Canada, seven of them at Perimeter. An additional four graduates are working with Perimeter's global outreach partners at various centres in the African Institute for Mathematical Sciences network. The majority of the remaining graduates have gone on to PhD programs at top international institutions, including Oxford, Princeton, and Caltech. Many of these alumni maintain ties to Perimeter through regular research visits.

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[10] This downward adjustment in enrolment reflects the Institute's assessment, after three years of running this intensive, interactive learning program, of the optimal class size.

[11] In 2011-12, the PSI faculty comprised 27 lecturers, including 15 Perimeter faculty and researchers, three DVRCs, and nine visiting international scientists.

PhD Students

- 35 PhD students were in residence at Perimeter in 2011-12
- Over the last year, two doctoral students supervised by Perimeter faculty graduated from the Institute's partner universities; both obtained competitive positions within Canadian industry
- Hoan Dang, a PhD student at Perimeter and the University of Waterloo, received a $150,000 Vanier Canada Graduate Scholarship to support his doctoral research

This year's increase in doctoral students is evidence of success in recruiting top PSI graduates for continued studies with Perimeter faculty, in line with the Institute's mid-term goals. As Perimeter is not a degree-granting institution, this talent gain is spread to the partner universities where students receive their degrees, thereby increasing the enrolment of top calibre students throughout the province.

Visiting Graduate Fellows Program (New Initiative)

- 10 Visiting Graduate Fellows came to Perimeter in 2011-12, with stays ranging from two to nine months in duration

This year, Perimeter launched the Visiting Graduate Fellows program to bring advanced PhD students from around the world to spend several months at the Institute, enabling them to join Perimeter's research community and interact with leading researchers at a pivotal time in their research training. The program has already been successful, and by January 2012, the program had achieved its steady state goal of hosting four to six Visiting Graduate Fellows at any given time.

Undergraduate Student Program

- Provided research training to eight exceptional undergraduate students from top international universities

The Undergraduate Student program exposes promising undergraduates to high-level research through two- to four-month projects, while giving Perimeter's postdoctoral researchers valuable mentoring experience. Since it was instituted in 2008, the program has also helped attract talent to Perimeter and to Canada, with several alumni returning to the Institute as visitors or members of the PSI master's program.

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

Summary of Achievements

- Recruited three leading scientists as Distinguished Visiting Research Chairs and renewed an additional seven to new three-year terms, which will bring the total to 26
- Appointed two accomplished researchers as Visiting Fellows and recruited two more for 2012-13, to bring the total to eight
- Hosted 401 visiting scientists for a total of 468 scientific visits, including 357 short-term scientific visitors, 21 long-term Visiting Researchers, 18 Distinguished Visiting Research Chairs, and five Visiting Fellows

Highlights

Distinguished Visiting Research Chairs Program

- 18 DVRCs made 35 visits to Perimeter in 2011-12

The Perimeter Distinguished Visiting Research Chairs (DVRC) program[12] is unique worldwide. While retaining permanent positions at their home institutions, DVRCs are appointed for three-year terms, during which they visit Perimeter for extended periods to do research, collaborate, lecture in the PSI program, and generally participate in all facets of Institute life. These world-leading scientists, such as Stephen Hawking, Nima Arkani-Hamed, Leonard Susskind, and Gerard 't Hooft, span an enormous range of expertise and greatly enhance Perimeter's research environment (see Appendix B, Distinguished Visiting Research Chairs). The DVRC program is also a valuable recruitment tool: BMO Financial Group Isaac Newton Chair Xiao-Gang Wen and senior Faculty member Guifre Vidal were both DVRCs prior to joining Perimeter full-time.

Seven DVRCs whose terms were expiring were renewed through 2015,[13] and Perimeter appointed three new DVRCs in 2011-12, as follows:

Adrian Kent (PhD Cambridge, 1996) is a Reader in Quantum Physics with the University of Cambridge and will join Perimeter as a DVRC in August 2012. He has previously held positions as an Enrico Fermi

[12] This was formerly called the Distinguished Research Chairs (DRC) program.
[13] Those renewed are: Yakir Aharonov, Nima Arkani-Hamed, Ignacio Cirac, Stephen Hawking, Renate Loll, Subir Sachdev, and Leonard Susskind. Three DVRCs – Neta Bahcall, Gia Dvali, and Ashoke Sen – were not renewed, while Xiao-Gang Wen's term as a DVRC ended when he moved to Perimeter full-time as the BMO Financial Group Isaac Newton Chair.

postdoctoral fellow at the University of Chicago, a member of the Institute for Advanced Study, and a Royal Society University Research Fellow at the University of Cambridge. He is just finishing an Associate Faculty position with Perimeter Institute. Kent's research focuses on the foundations of physics, quantum cryptography, and quantum information theory, including the physics of decoherence, novel tests of quantum theory and alternative theories, and new applications of quantum information.

Ramesh Narayan (PhD Bangalore, 1979) is the Thomas Dudley Cabot Professor of the Natural Sciences at Harvard University and will join Perimeter as a DVRC in September 2012. He is an astrophysicist who has won international renown for his research on black holes. Narayan has also carried out research in a number of other areas of theoretical astrophysics, including accretion disks, gravitational lensing, gamma-ray bursts, and neutron stars. He is a Fellow of the Royal Society (London), a Fellow of the American Association for the Advancement of Science, and a member of the International Astronomical Union and the American Astronomical Society.

Ashvin Vishwanath (PhD 2001, Princeton) is an Associate Professor in the Department of Physics at the University of California, Berkeley, and he joined Perimeter as a DVRC in January 2012. His primary field is condensed matter theory, with a focus on magnetism, superconductivity, and other correlated quantum phenomena in solids and cold atomic gases. Vishwanath is particularly interested in novel phenomena, such as topological phases of matter, non-fermi liquids, and quantum spin liquids. He has recently been interested in realizing Majorana and Weyl fermions in solids and in using concepts from quantum information, such as entanglement entropy, to characterize novel phases of matter. His past honours include a Sloan Research Fellowship (2004), the CAREER Award of the National Science Foundation (2007), the Outstanding Young Scientist Award of the American Chapter of Indian Physicists (2010), and the Simons Foundation Sabbatical Fellowship (2012).

Visiting Fellows Program

- Five Visiting Fellows made a total of nine visits to Perimeter in 2011-12

The Visiting Fellows program brings accomplished researchers to the Institute on a regular basis. Following the blueprint of the DVRC program, Visiting Fellows span a wide range of expertise, are appointed for three-year terms, and maintain their positions at other institutions while coming to Perimeter for extended research visits of up to six months each year.

In line with targeted objectives, Perimeter appointed two new Visiting Fellows in 2011-12 – Ruth Gregory and Neal Weiner – and recruited two more – Razvan Gurau and David Skinner – to begin in 2012-13. The new Visiting Fellows are:

Ruth Gregory joined Perimeter as a Visiting Fellow in October 2011. She is a professor in the Departments of Physics and Mathematical Sciences at Durham University, whose research centres on the interface between fundamental high energy physics and cosmology. Her recent work has been to try to explore simple braneworld models to determine what physical features they can have. In 2006, she was awarded the Maxwell Medal of the Institute of Physics (UK). Gregory has lectured on the PSI master's program for the past three years.

Razvan Gurau will become a Visiting Fellow in October 2012, when he takes up a junior faculty position at the Centre National de la Recherche Scientifique in France. Gurau received his PhD from the University of Paris in 2007 and has held postdoctoral positions at Perimeter since 2008. His research interests lie in mathematical physics, particularly in both perturbative and non-perturbative aspects of the renormalization of quantum field theories. His work is relevant for physics problems ranging from quantum gravity to condensed matter. For his work in quantum gravity, Gurau won the Hermann Weyl Prize for 2012.

David Skinner will become a Visiting Fellow in September 2012, when he joins the University of Cambridge as a tenure-track University Lecturer. He received his PhD from the University of Oxford in 2003 and has held postdoctoral positions at Perimeter since 2009. Skinner is interested in mathematical aspects of quantum field theories, particularly their overlap with twistor theory and string theory. His recent work explores the rich geometric structures present in the scattering amplitudes of four-dimensional gauge theory.

Neal Weiner joined Perimeter as a Visiting Fellow in January 2012. He is an Associate Professor of Physics at the Center for Cosmology and Particle Physics (CCPP) at New York University. After receiving his PhD from UC Berkeley in 2000, Weiner was a postdoc at the University of Washington from 2000 to 2004, joining the CCPP at NYU in the fall of 2004. He has broad interests in particle physics and cosmology, with a general focus on physics beyond the Standard Model. In this broad field, his work has included studies of extra dimensional theories (large, small, warped, and flat), supersymmetry, grand unification, flavor, neutrino mass, dark matter, inflation, and dark energy, as well as relationships between the different subjects.

Visitor Program

- Perimeter hosted 401 visiting scientists who made a total of 468 scientific visits, including 357 short-term scientific visitors, 18 Distinguished Visiting Research Chairs, and five Visiting Fellows[14]
- Twenty-one long-term Visiting Researchers accepted invitations to work at Perimeter during leaves of absence from their home institutes

Perimeter Institute's active visitor program enables its resident scientists to stay abreast of recent developments, exchange ideas, and spark new collaborations. Visiting researchers, meanwhile, benefit from having the time and space for the intense, sustained work required to tackle tough problems. The program is also a recruitment aid, showcasing the Institute's vibrant research environment and the

[14] These 18 DVRCs accounted for 35 visits, including three visits to lecture in the PSI program. The five Visiting Fellows made a total of nine visits.

excellent administrative support that enables scientists to maximize productivity. In the past year, visits by Dmitry Abanin and Kendrick Smith were critical in persuading them to join Perimeter's faculty.

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

Summary of Achievements

- Partnered on seven workshops and conferences held at Perimeter and other institutions, and sponsored an additional 11 off-site conferences, workshops, and symposia (see Objective 8)
- Concluded two new partnerships with the ICTP-South American Institute for Fundamental Research in Sao Paolo, Brazil, and the Institute of Mathematical Sciences in Chennai, India
- Provided extensive support to the African Institute for Mathematical Sciences-Next Einstein Initiative (AIMS-NEI)

Highlights

Collaborations and Partnerships

In 2011-12, the Institute continued to strengthen existing partnerships within Canada and abroad, while providing scientific opportunities for Perimeter researchers. Fruitful collaborations continue with institutes like the Centre for Theoretical Cosmology (CTC) at Cambridge, the Abdus Salam International Centre for Theoretical Physics (ICTP), TRIUMF, the LIGO Scientific Collaboration, and the HoloGrav Network in Europe.

In addition, some highlights from the past year include:

- **"Integrability in Gauge and String Theory"** (July 31-August 19, 2011): This innovative three-week program was held through the UNIFY partnership and brought more than 170 graduate students, postdoctoral researchers, and senior scientists together at Perimeter.[15] Since 2010, Perimeter's partnership with the Centro de Física do Porto (CFP) in Portugal has facilitated the organization of the "Mathematica Summer School" that kicked off this program.

- **"Cape Town International Cosmology School"** (January 15-28, 2012): Perimeter, along with partners from ICTP and AIMS, helped sponsor this two-week introduction to modern cosmology, held at the Stellenbosch Institute for Advanced Studies in South Africa. Perimeter Associate

[15] The Unification of Fundamental Forces and Applications (UNIFY) includes seven partnering institutions spanning three continents: Humboldt-Universität zu Berlin, Commissariat à l'Énergie Atomique et aux Énergies Alternatives – Saclay (France), Universidade do Porto (Portugal), Institute for the Physics and Mathematics of the Universe (IPMU) at the University of Tokyo, California Institute of Technology (Caltech), the Yang Institute for Theoretical Physics at the State University of New York (SUNY), and Perimeter Institute.

Faculty member Niayesh Afshordi was one of the speakers at the school, which was aimed at PhD students and postdoctoral researchers.

- **"Cosmological Frontiers in Fundamental Physics 2012"** (May 29-June 1, 2012): 2012 marked the sixth workshop in a series organized jointly by Perimeter Institute, the Laboratoire Astroparticule et Cosmologie (APC) in Paris, France, and the International Solvay Institutes in Brussels, Belgium. The 2012 edition of the workshop was held in Brussels and focused on holographic/string cosmology and related topics.

- **"Back to the Bootstrap II"** (June 11-15, 2012): This workshop devoted to conformal field theories featured a number of researchers tied to the UNIFY partnership, including Scientific Organizers Joao Penedones (Porto), Leonardo Rastelli (SUNY), and Pedro Vieira (Perimeter).

In line with targeted objectives, Perimeter also concluded two new partnership agreements in 2011-12, forging new scientific connections to Brazil and India.

International Centre for Theoretical Physics-South American Institute for Fundamental Research (ICTP-SAIFR), Brazil

In April 2012, Perimeter signed an agreement with the International Centre for Theoretical Physics-South American Institute for Fundamental Research (ICTP-SAIFR) to promote academic ties between the two institutes. ICTP-SAIFR is a recently-created South American centre for theoretical physics located at the State University of São Paolo in Brazil. The one-year agreement will facilitate scientific visits and encourage collaboration on workshops, and will be re-evaluated after one year with the intent of renewing it on a mutually agreeable basis.

Institute of Mathematical Sciences (IMSc), India

In July 2012, Perimeter signed a memorandum of understanding with the Institute of Mathematical Sciences (IMSc) in Chennai, India, to promote progress in research areas of common interest and encourage academic ties between both institutes. IMSc promotes fundamental research in theoretical physics, mathematics, and theoretical computer science, as well as in many interdisciplinary fields. The one-year agreement, which is expected to be renewed on a mutually agreeable basis, encourages scientific exchange visits and collaborations between researchers at Perimeter and IMSc.

Global Outreach

Perimeter Institute's Global Outreach initiative shares expertise (not funding), in order to help catalyze the growth of centres of excellence in theoretical physics and math around the world. In 2011-12, Perimeter's Global Outreach focus continued to be the African Institute for Mathematical Sciences-Next Einstein Initiative (AIMS-NEI), the pan-African initiative founded in 2003 by Perimeter Director Neil

Turok to establish a network of centres providing advanced mathematical and scientific education to the continent's most exceptional graduates.

The Global Outreach program has facilitated a flow of researchers and students between Perimeter and Africa. A number of researchers have gone to AIMS centres as tutors and lecturers, including four graduates of the 2011-12 class of Perimeter Scholars International (PSI). To date, four AIMS graduates have entered the PSI program, a number expected to increase as more AIMS centres open.

Perimeter provided staff support and expertise to AIMS-NEI in various ways over the past year, including the following:

- Enlisted the University of British Columbia in the "One for Many" campaign to provide scholarship funds for AIMS students, pledging $100,000 over five years
- In February 2012, helped organize a workshop devoted to AIMS and the acceleration of young talent in the developing world at the Annual Meeting of the American Association for the Advancement of Science (AAAS), the world's largest yearly gathering of science researchers, educators, policy makers, and journalists
- Welcomed AIMS-NEI staff to Perimeter and provided training on various aspects of organizational planning and management
- Sent senior Perimeter staff members to AIMS centres to advise on outreach and management practices, as well as provide building expertise tied to the September 2011 opening of AIMS-Senegal and the August 2012 opening of AIMS-Ghana

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

Summary of Achievements

- Increased engagement with experimental and observational centres in Canada
- Appointed 17 new Affiliate members, bringing the total to 119 at the end of 2011-12
- Conducted joint faculty searches with the University of Waterloo and York University, resulting in the recruitment of two new Associate Faculty members (see Objective 2)
- Launched two new scientific resources that will aid collaborative research efforts in the broader physics community (see Objective 3)
- Partnered with the University of Waterloo to deliver the PSI master's program and involved faculty from Canadian universities as lecturers[16] (see Objective 4)
- Partnered on seven workshops and conferences held at Perimeter and other institutions, and sponsored an additional 11 off-site conferences, workshops, and symposia (see Objective 8)
- Held five courses open to students at surrounding universities (see Objective 8)

Highlights

Perimeter Institute is a hub of theoretical physics research in Canada. In 2011-12, the Institute continued to provide unique resources to the national scientific community through the courses, seminars, workshops, and conferences it held (see Objective 8). It brought top talent to Canada at all levels, from the students coming to Perimeter through the PSI master's program (see Objective 4) to the joint recruitment of postdoctoral researchers (see Objective 4)[17] and associate faculty (see Objective 2).[18] Perimeter continued to cultivate strategic partnerships at all levels, including the sponsorship and co-organization of conferences (see Objective 6), engagement with experimental and observational centres, and recruitment of new Affiliate members (see below).

Engagement with Experimental Centres

In 2011-12, Perimeter delivered on its major targeted outcome, continuing to pursue joint opportunities with experimental and observational centres in Canada. Recognizing that experiment provides the ultimate test of all theory, Perimeter has continued to strengthen ties with the experimental partner institute it helped establish, the Institute for Quantum Computing (IQC) at the University of Waterloo. New Associate Faculty member Roger Melko is an affiliate at IQC, while Faculty recruit Dmitry Abanin

[16] David Morrissey, TRIUMF; Veronica Sanz, York University.

[17] Tim Johannsen will split his time between Perimeter, the Canadian Institute for Theoretical Astrophysics, and the University of Waterloo.

[18] Roger Melko was jointly appointed with the University of Waterloo, while Matthew Johnson became the Institute's first associate faculty member jointly appointed with York University.

plans to spend one day a week at IQC upon his arrival in 2012-13. Associate Faculty members David Cory, Raymond Laflamme, and Michele Mosca continue to be key members of IQC's faculty, which also includes three of Perimeter's newest Affiliates, Adrian Lupascu, Hamed Majedi, and Ashwin Nayak. With such a wealth of connections, ongoing research collaborations between the two institutes have been an inevitable outgrowth.

Perimeter has also increased ties to other experimental partners in Canada, including TRIUMF and SNOLAB, laboratories for particle and nuclear physics. In July 2012, Perimeter, TRIUMF, and SNOLAB sent a joint letter to the Government of Canada encouraging the Minister of State (Science and Technology) to consider more formal ties to the European Organization for Nuclear Research (CERN), such as Associate Membership. In this way, Perimeter is working with Canada's top experimental centres for particle physics to try to give the country a larger role in the world's largest experiment, the Large Hadron Collider (LHC) at CERN.

Perimeter is already successfully engaging with experimentalists at the LHC. In April 2012, the Institute hosted nearly 40 leading theorists and experimentalists from around the world for the "Higgs: Now and in the Future" conference.[19] Faculty members Philip Schuster and Natalia Toro have established highly productive collaborative ties to experimentalists at the LHC and, in 2011-12, the Institute formally launched its "Get Out" (GO) Program for postdoctoral researchers in particle physics, which enables them to work with experimental peers at centres like CERN, TRIUMF, and SNOLAB.

Affiliate Member Program

In 2011-12, Perimeter added 17 new Affiliate members across the country, exceeding targeted outcomes and bringing the total to 119. Affiliates are select researchers at Canadian universities who are invited for regular informal visits to Perimeter for scientific collaboration and the opportunity to be involved in the Institute's research activities. The program continues to strengthen regional and national research linkages between Perimeter and the Canadian scientific community, while in turn enriching the Institute's research environment (see Appendix C, Affiliate Members).

[19] This conference included scientists from many top Canadian institutions: TRIUMF, Carleton University, McMaster University, Simon Fraser University, and the Universities of Alberta, British Columbia, Montreal, Toronto, and Victoria.

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

Summary of Achievements

- Held 17 timely, focused conferences and workshops, attended by 1,013 scientists from around the world
- Partnered on seven conferences and workshops with national and international partners, while sponsoring an additional 11 (see Objective 7)
- Presented 299 scientific talks (271 seminars, 28 colloquia)
- Delivered five courses to researchers and students from surrounding universities

Highlights

Conferences and Workshops

- In 2011-12, Perimeter held 17 focused conferences and workshops, including two with over 100 participants, exceeding targeted outcomes[20]

Perimeter holds timely, focused conferences and workshops on some of the most cutting-edge research in theoretical physics, prioritizing topics with high potential for stimulating significant outcomes. More than 1,000 scientists from around the world visited Perimeter this year, underlining its role as a major node of exchange for theoretical physics globally. The conference program also strengthens ties with institutional partners, as evidenced by the fact that Perimeter partnered on seven conferences with national and international partners in 2011-12.[21] The Institute sponsored 11 additional conferences throughout Canada and abroad.[22]

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[20] These two larger conferences were “Exact Results in Gauge/Gravity Dualities” (August 8-12, 2011; 106 attendees, including DVRCs Nima Arkani-Hamed and Leo Kadanoff) and “Integrability in Gauge and String Theory” (August 15-19, 2011; 129 attendees, including DVRCs William Unruh, Nima Arkani-Hamed, and Sandu Popescu), both of which were part of the IGST 2011 program.

[21] These included “Emergence and Effective Field Theory” (with the Rotman Institute at Western University); “Recent Progress in Quantum Algorithms” (with the Institute for Quantum Computing at the University of Waterloo); “GAP 2012” (with the University of Waterloo); “Canadian Society for the History and Philosophy of Science” (with the University of Waterloo); “Cosmological Frontiers in Fundamental Physics 2012” (with the International Solvay Institutes in Brussels, Belgium, and the APC in Paris, France); “Background and Methods of Highly Frustrated Magnetism 2012” (with McMaster University); and “Relativistic Quantum Information” (with the University of Waterloo).

[22] 1. QIP 2012; 2. PI-ICTP-AIMS Cosmology School;3. Lake Louise Winter Institute 2012;4. Theory Canada 7; 5. QI 2012 Summer School; 6. 9th Canadian Student Conference on Quantum Information; 7. 14th Canadian Conference

Among the groundbreaking conferences hosted at the Institute in the past year, highlights included:

- **"Integrability in Gauge and String Theory"** (July 31-August 19, 2011): This three-week program consisted of three distinct phases, each with 80 to 130 participants, organized around this cutting-edge area. It began with the "Mathematica Summer School," which brought together physicists of all levels to learn *Mathematica* software while doing advanced research problems in scattering amplitudes. Next was a five-day workshop on "Exact Results in Gauge/Gravity Dualities." Finally, a formal conference, "Integrability in Gauge and String Theory," was held to exchange new ideas on this rapidly evolving field.
- **"Emergence and Effective Field Theory"** (October 26-28, 2011): This interdisciplinary workshop focused on ideas from effective field theories as they are applied to many areas of physics, including condensed matter physics, cosmology, high energy physics, string theory, and quantum gravity. DVRC Leo Kadanoff was one of the workshop's scientific organizers and fellow DVRCs Ganapathy Baskaran and William Unruh participated.
- **"Higgs: Now and in the Future"** (April 23-24, 2012): This conference exemplified the cross-fertilization of ideas between theory and experiment Perimeter seeks to foster. In advance of July's announcement confirming the discovery of the Higgs boson, Perimeter brought together a group of leading experimentalists (mostly from the ATLAS collaboration at the Large Hadron Collider) and theorists for a two-day workshop aimed at understanding recent Higgs-related developments and paving the way forward.

Seminars and Colloquia

- Perimeter held 271 seminars and 28 colloquia in 2011-12, exceeding targeted outcomes

Seminars and colloquia foster collaboration and share knowledge from leading researchers around the globe, invigorating the Institute's research community. Particularly notable from the past year were talks by DVRCs Yakir Aharonov, James Bardeen, Ganapathy Baskaran, Ramesh Narayan, Frans Pretorius, Subir Sachdev, Senthil Todadri, William Unruh, Ashvin Vishwanath, and Mark Wise. Higher than anticipated numbers were largely due to a marked increase in the number of scientific talks given by potential recruits while visiting Perimeter.

on General Relativity and Relativistic Astrophysics; 8. 60^{th} Birthday Conference in Honour of John Preskill; 9. Women in Physics Canada;10. Canadian Prairie Theoretical Physics Network; 11. Laser Physics Workshop 2012.

Perimeter Institute Recorded Seminar Archive (PIRSA)

- In 2011-12, 75,369 unique visitors from 166 countries accessed PIRSA, a 47 percent increase over last year

Nearly all talks held at Perimeter can be viewed online on PIRSA, the Perimeter Institute Recorded Seminar Archive at www.pirsa.org. This permanent, free, searchable, and citable archive of video-recorded seminars, conferences, workshops, and courses was developed by the Institute to share knowledge with the international scientific community. It is an important scientific resource for the field, as evidenced by the continued rise in site traffic year over year. New and returning users are also accessing PIRSA more frequently, as demonstrated by the 37 percent increase in the number of visits over last year, representing 674,618 page views.

Courses

- In 2011-12, Perimeter offered five courses (four of them for-credit), meeting targeted outcomes

In addition to the three-week courses delivered through the PSI program, Perimeter's resident and visiting scientists give topical courses on cutting-edge areas, which are open to students of surrounding universities. Highlights included "Advanced General Relativity," taught by Eric Poisson (University of Guelph), and "Advanced Quantum Field Theory," taught by Perimeter Associate Faculty member Cliff Burgess.

Objective 9: To engage in high impact outreach

Summary of Achievements

- Hosted the 10th annual International Summer School for Young Physicists, held six one-day *GoPhysics!* camps, and gave 14 *Physica Phantastica* presentations to over 2,100 students across Canada
- Delivered 85 workshops to more than 3,300 educators throughout Canada and abroad, impacting over 180,000 students
- Hosted over 200 participants at the Ontario Association of Physics Teachers' annual conference
- Completed two new in-class and web-based educational resources
- Authored the modern physics unit of the grade 12 physics textbook tied to Ontario's curriculum
- Held three days of grand opening festivities for the Stephen Hawking Centre, attended by over 10,000 on-site visitors and thousands more online and on television
- Held the BrainSTEM unconference to foster innovation in science communication
- Presented 11 Public Lectures
- Released and distributed the *Equinox Blueprint: Energy 2030* to over 1,200 stakeholders worldwide
- Played an active role on "Team Canada" at the annual meeting of the American Association for the Advancement of Science (AAAS)

Highlights

Student Programs and Products

International Summer School for Young Physicists (ISSYP)

- Held the 10th successful year of ISSYP for 39 top Canadian and international students[23]

The International Summer School for Young Physicists (ISSYP) brings talented Canadian and international students to Perimeter for two weeks of intensive study in modern physics, including mentoring sessions and lab tours. By providing a first-hand view of leading-edge research at an age when students are actively weighing career directions, Perimeter strives to develop new talent for the field and for Canada.[24] Follow-up metrics indicate that it is successful, with over 70 percent crediting ISSYP with inspiring them to pursue a career in math or physics.

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[23] This included 20 Canadians from nine provinces and 19 international students from 11 countries.
[24] Follow-up surveys indicate that ISSYP alumni have gone on to study at a host of top international institutions – including Cambridge, MIT, Stanford, Harvard, Princeton, and CERN – as well as a long list of Canadian universities:

A spirit of continual improvement lies at the heart of ISSYP's success. Thus, in 2011, with multi- year support from the RBC Foundation, Perimeter hired an Educational Consultant to refine ISSYP's curriculum and gather its rich content into a modern physics textbook for broader use. As a result, the 2012 edition began moving away from conventional lectures toward experiences that more closely model the true nature of scientific research, and participants gave feedback on the first few chapters of the new text.

GoPhysics!

- In 2011-12, Perimeter held six *GoPhysics!* camps across Canada[25]

GoPhysics! is a one-day program that gives a snapshot of the ISSYP experience to approximately 25 students at a time. Given by Teacher Network Associates and Perimeter's Outreach staff scientists, it is designed to get high-potential senior high school students excited about modern physics.

Physica Phantastica Presentations

- Staff delivered 14 large-scale presentations to over 2,100 students across the country in 2011-12, exceeding targeted outcomes

Physica Phantastica presentations provide entertaining and accessible introductions to modern physics, designed to captivate and inspire through the exploration of cosmic mysteries. Though the focus of *Physica Phantastica* presentations will remain on students in grades 7 to 12, Perimeter also gave two presentations to adult audiences by request: the Ontario Association for Mathematics Education (OAME) and the Waterloo Region District School Board (WRDSB) math teachers.

Aboriginal Engagement

- In July 2012, Actua partners delivered Perimeter content to 955 Aboriginal youth in 61 rural and remote communities

After researching the most effective ways to engage Aboriginal teachers and students across Canada, Perimeter has developed an action plan that involves partnering with Actua, Canada's leading national science, technology, engineering, and mathematics (STEM) outreach organization for youth. In fact, Perimeter has already begun implementing this delivery strategy: in 2012, the Institute's outreach staff

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Acadia, Alberta, Brandon, British Columbia, Calgary, Carleton, Dalhousie, Guelph, Manitoba, McGill, McMaster, Memorial, Mount Allison, Prince Edward Island, Queen's, Saint Mary's, Saskatchewan, Toronto, Victoria, Waterloo, Western, Wilfrid Laurier, and Windsor (as well as Perimeter Scholars International).

[25] In Victoria, Regina, Brampton, Uxbridge, Charlottetown, and St. John's

trained Actua associates from across Canada on Perimeter's resources, with a pilot project targeting elementary schools in northern Ontario, northern British Columbia, Northwest Territories, and Nunavut.

Programs and Resources for Teachers

EinsteinPlus National Teachers' Workshop

- 52 high school teachers (43 Canadians and nine international teachers) participated in the 2012 EinsteinPlus National Teachers' Workshop (E+)

This intensive, one-week workshop is the primary hub for Perimeter's extensive engagement with Canada's physics educators. It shares effective strategies for teaching key modern physics concepts, facilitates peer exchange of proven teaching methods, and tests Perimeter's in-class resources in development, ensuring they are based in sound pedagogy and will have an impact in the classroom. Surveys of E+ participants indicate that the experience is a top-calibre professional development opportunity and an effective means of distributing the Institute's educational resources.

Teacher Network

- Network Associates delivered 65 workshops to 1,500 educators, thereby reaching 112,500 Canadian high school students in 2011-12, in line with targeted outcomes

E+ alumni form the core of Perimeter's Teacher Network, which is crucial in extending the reach of the Institute's resources. The Network is comprised of over 60 teachers throughout Ontario and across Canada who train fellow educators in their home districts on how to share Perimeter's educational modules.

On-location Teacher Workshops

- Delivered 18 on-location workshops at teacher conferences nationally, exceeding targeted outcomes and reaching over 1,800 educators[26]

Presentations at educational conferences and gatherings have proven to be an effective way of increasing the visibility and reach of the Institute's outreach products and programs, both within Canada

[26] The conferences Perimeter staff presented at included British Columbia's Science Teaching Catalyst Conference and the annual conferences of the Science Teachers' Association of Ontario (STAO) and the Science Teachers' Association of Manitoba (STAM).

and abroad. In April 2012, Perimeter hosted over 200 educators for the annual conference of the Ontario Association of Physics Teachers (OAPT), the highest participation rate in OAPT history.

Outreach staff again presented workshops internationally at the Physics Teaching Resource Agents' (PTRA) annual Summer National Leadership meeting and the High School Teachers (HST) Program at CERN in Switzerland for more than 50 European physics teachers from over 20 countries. Staff also delivered several presentations to elementary and junior high school teachers, part of a strategic effort to expand Outreach efforts into younger grades.[27]

Educational Resources

Perimeter Inspirations and *Explorations*

- Completed two new in-class modules in 2011-12: *Process of Science* and *Beyond the Atom – Remodelling Particle Physics*

Perimeter's in-class educational modules have cumulatively reached over one million students across Canada to date. Produced with the input of physics educators and scientists, they are the Institute's primary means of introducing Canadian high school students to modern physics. Feedback indicates they are used and re-used in classrooms.

Perimeter employs a balanced approach to educational product creation. *Perimeter Inspirations* modules aim to inspire elementary and junior high school students to continue with math and science in later grades, while *Perimeter Explorations* deliver more challenging ideas and technical content to senior high school students, providing excellent preparation for post-secondary education in math, science, and engineering.

Process of Science is the newest addition to the *Inspirations* series, showcasing the habits of mind that scientists practice in their search for answers. ***Beyond the Atom – Remodelling Particle Physics*** is an *Explorations* module that deals with one of the hottest topics in physics, detailing the advances in our understanding of the building blocks that comprise the cosmos. This latest *Explorations* resource was completed in both French and English this year.

Also this year, sections from past Perimeter resources – including *Revolutions in Science*, *The Challenge of Quantum Reality*, and *Measuring Planck's Constant* – were incorporated into *Physics 12*, the only grade 12 textbook tied to the Ontario curriculum. It is expected to reach every physics student in the province for years to come.

[27] Perimeter developed the *Process of Science* module specifically for elementary and junior high school students and further expanded its engagement with younger grades through the *Alice and Bob in Wonderland* resource. The outreach team specifically targeted two sessions at STAO toward teachers of the younger grades and participated in a September 2011 Professional Development day for regional elementary school teachers. Staff also trained associates at Actua, a leading Canadian science outreach organization for youth, who in turn trained students across the country during their summer programming.

Perimeter continues to develop new content and search for ways to extend their reach. Work has just begun on a new *Explorations* module related to careers in science, which will continue through 2012-13 for delivery the following year. Meanwhile, in an effort to increase Perimeter's brand internationally, the Institute is investigating the possibility of expanding the distribution of its resources worldwide.

Online Resources

Perimeter Institute has long prioritized offering digital versions of its key programs and products as a means of scaling its reach and impact. The list of high-quality resources available on the Institute's website include *Perimeter Inspirations* and *Explorations*, *Virtual ISSYP*, more than 30 *Meet A Scientist* videos, and an archive of past Public Lectures (which are also available through iTunes University).

In 2011-12, the outreach team continued to update and expand Perimeter's online resources, allowing the Institute to efficiently and cost-effectively reach more students. Perimeter held 12 webinars with students and teachers across the country over the last year.[28]

Perimeter expanded its social media network this year via targeted, engaging content sharing, primarily through Facebook, Twitter, and YouTube. In this regard, an online contest to be promoted through social media that was planned for the 2011-12 fiscal will instead be held in early 2012-13 in light of the superior opportunity presented by Perimeter Director Neil Turok's Massey Lectures.

The outreach team also developed new content for webcasts on special topics, meeting targeted objectives. Of note, a hot topic webinar held to explain new results from the Large Hadron Collider attracted over 1,100 live viewers and more than 10,000 visitors from dozens of countries around the world in the days that followed. It was also featured on *Scientific American*'s homepage and continues to be accessed for playback.

BrainSTEM unconference

In June 2012, in collaboration with Waterloo-based Communitech, Perimeter hosted the **BrainSTEM unconference**. The invitation-only summit connected science video creators, educators, and outreach experts for two days of intense discussion on the state of science education. The event put Perimeter at the forefront of the exploding area of online science, engaging a group of content creators with over 300 million YouTube views and over 2.5 million subscribers collectively. Lessons learned will help to inform the Institute's online engagement efforts going forward, but the benefit has already spread to Perimeter's education partners, whose eyes were opened to a high-quality means of engaging students in an online forum students already use.

[28] This includes seven webinars held with teachers from across the country and five for students in Edmonton, Calgary, Toronto, Uxbridge, and Halifax.

Major Events and Programs for the General Public

Grand Opening of the Stephen Hawking Centre at Perimeter Institute

- Over 10,000 visitors, including local, provincial, and federal dignitaries, attended the grand opening weekend of the Stephen Hawking Centre

In September 2011, Perimeter celebrated the opening of the Stephen Hawking Centre with three days of festivities designed to thank public and private partners, and to share the excitement of science with the public. The weekend included four Public Lectures, tours of the facilities, hands-on exhibits, and a special event celebrating the life and work of Distinguished Visiting Research Chair Stephen Hawking, who participated via a video link. In addition to on-site attendance, key events were broadcast online and on TV to thousands more.

The grand opening received widespread media coverage, including a two-page story in *The Globe and Mail* and a cover story in *The National Post* (Saturday, September 17, 2011 editions). Overall, online and print readership of the event's coverage was estimated in excess of two million, and the *Stephen Hawking: The Power of Ideas* television broadcast continues to be viewed online, with over 40,000 views via YouTube alone.[29]

Public Lecture Series

- 11 accessible, engaging talks on compelling scientific topics were presented in 2011-12

The Perimeter Public Lecture Series, presented by Sun Life Financial, continues to be extremely popular, with all 600 tickets consistently 'selling out' within minutes (although the lectures are free, admission requires tickets ordered in advance through Perimeter's website). Highlights of the 2011-12 season included Canadian astronaut Julie Payette, who spoke on research and collaboration in space; science historian George Dyson on the origins of the digital universe; Fay Dowker of Imperial College, who spoke about black hole thermodynamics; author Graham Farmelo on the famously eccentric Paul Dirac; and independent physicist Julian Barbour on the topic, "Does Time Exist?"

Perimeter continued to partner with TVO in 2011-12, allowing all lectures to be professionally recorded and later broadcast on "Big Ideas," as well as online through TVO, Perimeter's website, and iTunes University. Through this partnership, TVO also broadcast "Stephen Hawking: The Power of Ideas." They report that Perimeter content is among their most popular science offerings.

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[29] Refer to Appendix F: Media Highlights for a summary of the media coverage throughout 2011-12, including the grand opening.

Waterloo Global Science Initiative (WGSI)

The Waterloo Global Science Initiative (WGSI) is an independently funded, non-profit partnership between Perimeter Institute and the University of Waterloo whose mandate is to catalyze scientific and technological solutions to key challenges. WGSI's inaugural conference, *Equinox Summit: Energy 2030*, held in June 2011, brought together scientists, policy experts, entrepreneurs, and young leaders from around the world to explore new technologies for the production, storage, and distribution of electric power.

In February 2012, in line with targeted outcomes, the *Equinox Blueprint: Energy 2030* was released, summarizing the recommendations of WGSI conference participants on potentially transformative technologies and strategies for their implementation. The report garnered significant coverage from major international media organizations, including a two-page feature in Canada's *Globe and Mail*; it was also presented at the Annual Meeting of the American Association for the Advancement of Science. The report has been provided to more than 1,200 stakeholders worldwide, including global science and technology leaders in industry and government.

American Association for the Advancement of Science (AAAS) and Science Media

The American Association for the Advancement of Science (AAAS), the world's largest general science gathering, held its annual meeting in Vancouver in February 2012. This marked the first time the meeting has been held outside of the US in 30 years. It attracted over 6,000 people tied to science research, policy, education, and the media, giving Perimeter an excellent opportunity to showcase Canadian success in research, training, and outreach, while building relationships with science communication colleagues.

As a key member of "Team Canada," Perimeter played a role in raising the visibility of basic research, by presenting several lectures, panels, and workshops. Highlights included remarks by AAAS Co-Chair (and PI Director) Neil Turok, Founder and Board Chair Mike Lazaridis' plenary talk on the importance of science and education, two panels co-presented with the African Institute for Mathematical Sciences and the Institute for Quantum Computing, and an innovation themed gathering for international media.

In addition to its involvement in the AAAS annual meeting, Perimeter continued to support the development of science media as a program sponsor of the Science Communication Program at the Banff Centre and as a Charter Member of the Science Media Centre of Canada.

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

Summary of Achievements

- Finalized federal funding agreement of $50 million, beginning in 2012
- Finalized provincial funding agreement of $50 million, beginning in 2011
- Secured $2 million grant from the John Templeton Foundation
- Attracted nearly $1.2 million in cash, plus $600,000 in in-kind donations
- Secured $4 million commitment from a private foundation

Highlights

Public Funding

Perimeter is funded through an innovative public-private partnership. To date, contributions from both sides of this partnership have been approximately equal, and Perimeter has gained global recognition for its funding model, which shares the opportunities and benefits of long-term investment in fundamental research.

Investment from all levels of government helped establish Perimeter and sustained support from the public sector has been critical to the Institute's success to date. In 2011-12, Perimeter welcomed the renewed support of the Government of Canada and the Province of Ontario through finalized funding agreements. The federal government grant agreement provides $50 million beginning in 2012, while the provincial investment provides $50 million starting in 2011.

Private Sector Funding

New private sector donations from individuals and corporations increased significantly from $231,000 to $727,000 in 2011-12, with an additional commitment of $4 million from a private foundation. To drive private sector donations, the Institute created a number of new funding circles; **The Director's Circle**, for example, provides support for operations through donations of $1,000 to $250,000, and attracted $172,000 in 2011-12. The **Emmy Noether Circle** directs donations to supporting women in science and received over $50,000.

The Institute also pursues funding from foundations and received $45,000 in 2011-12. In addition, Perimeter obtained a $2 million grant over three years from the John Templeton Foundation to create the **Templeton Frontiers Program at Perimeter Institute**. The program will support postdoctoral fellows, visiting researchers, and conferences in three research areas which are key to major advances in our understanding of the universe: quantum foundations and information, foundational questions in cosmology, and the emergence of spacetime.

New funding from corporations, including Burgundy Asset Management, Canadian Tire Corporation Ltd., Scotiabank, and CIBC Mellon, increased in 2011-12 to $503,000. In addition, $589,000 worth of in-kind donations were received, including a state-of-the-art multimedia display wall worth $410,000 from Christie Digital.

Finally, several existing corporate and foundation sponsors renewed their investments in 2011-12, including the following:

- Sun Life Financial renewed its $100,000 per year support of the Perimeter Public Lecture Series through the 2012-13 season
- RBC Foundation has just completed the second year of a four-year $400,000 pledge in support of the International Summer School for Young Physicists
- The Cowan Foundation again gave $25,000 toward *Perimeter Inspirations* resources for students
- The Kitchener and Waterloo Community Foundation – Musagetes Fund provided an additional $20,000 in support of Perimeter's cultural programming in 2011-12

Perimeter Research Chairs

The Perimeter Research Chairs are a keystone of the Institute's strategic expansion plan. The Institute aims to create five such chairs, each worth $4 million, named after Newton, Maxwell, Euler, Einstein, and Bohr. The BMO Financial Group Isaac Newton Chair at Perimeter Institute has already been funded and, in May 2012, the Institute welcomed world-renowned condensed matter theorist Xiao-Gang Wen (previously of MIT) as the inaugural chairholder (see Objective 2). In 2011-12, Perimeter also secured a pledge to fund the Euler Chair, which will be announced once an appropriate candidate has been officially recruited.

Leadership Council

The Perimeter Institute Leadership Council consists of 22 influential leaders, primarily from the private sector, who volunteer their time, offer guidance, and act as ambassadors for Perimeter in the business and philanthropic communities. The Council is strengthening Perimeter's circle of contacts beyond the high tech and academic sectors to include areas like finance, media, and major retail. In its second year of existence, the Leadership Council has engaged potential new members who would expand the group's geographic reach across Canada and into the US. Seventy percent of Council members are also donors.

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

Summarized Financial Statements of

PERIMETER INSTITUTE

Year Ended July 31, 2012

ZEIFMANS
LLP
CHARTERED ACCOUNTANTS

ZEIFMANS
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CHARTERED ACCOUNTANTS

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To the Directors of
Perimeter Institute

The accompanying summary financial statements, which comprise the summary statement of financial position as at July 31, 2012, the summary statement of operations and changes in fund balances for the year then ended, are derived from the financial statements of Perimeter Institute (the "Institute") as at, and for the year ended, July 31, 2012. We expressed an unmodified audit opinion on those financial statements in our report dated December 7, 2012. Those financial statements, and the summary financial statements, do not reflect the effects of events that occurred subsequent to the date of our report on those financial statements.

The summary financial statements do not contain all the disclosures required by Canadian generally accepted accounting principles. Reading the summary financial statements, therefore, is not a substitute for reading the audited financial statements of the Institute.

Management's Responsibility for the Summary Financial Statements

Management is responsible for the preparation of a summary of the audited financial statements in accordance with Canadian generally accepted accounting principles.

Auditor's Responsibility

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

Opinion

In our opinion, the summary financial statements derived from the audited financial statements of the Institute as at, and for the year ended, July 31, 2012 are a fair summary of those financial statements, in accordance with Canadian generally accepted accounting principles.

Zeifmans LLP

Toronto, Ontario
December 7, 2012

Chartered Accountants
Licensed Public Accountants

PERIMETER INSTITUTE
Summarized Statement of Financial Position
as at July 31, 2012

(in thousands of dollars)

	2012	2011
ASSETS		
Current Assets:		
Cash and cash equivalents	$ 1,697	$ 1,082
Investments	211,417	218,970
Government grants receivable	4,294	2,145
Other current assets	1,151	2,168
Assets held for sale	1,235	---
	219,794	224,365
Property and equipment	55,281	55,489
TOTAL ASSETS	$ 275,075	$ 279,854
LIABILITIES AND FUND BALANCE		
Current liabilities:		
Bank overdraft	$ 732	$ 577
Bank indebtedness	2,245	1,330
Accounts payable and other current liabilities	2,331	6,168
TOTAL LIABILITIES	5,308	8,075
Fund balances:		
Invested in capital assets	56,495	53,536
Externally restricted	105,589	100,128
Internally restricted	78,840	78,840
Unrestricted	28,843	39,275
TOTAL FUND BALANCES	269,767	271,779
	$ 275,075	$ 279,854

ZEIFMANS
LLP
CHARTERED ACCOUNTANTS

PERIMETER INSTITUTE
Summarized Statement of Operations and Changes in Fund Balances
For the Year Ended July 31, 2012

(in thousands of dollars)

	2012	2011
Revenue		
Government grants	$ 14,412	$ 18,190
Other income	741	425
Donations	1,142	212
	16,295	18,827
Expenses		
Research	11,025	9,748
Research training	1,838	1,688
Outreach and science communications	3,350	2,601
Indirect research and operations	5,641	4,535
	21,854	18,572
Excess of revenue over expenses (expenses over revenue) before investment income and amortization	(5,559)	255
Amortization	(4,098)	(1,573)
Investment income	7,645	20,940
Excess of revenue over expenses (expenses over revenue)	(2,012)	19,622
Fund balances, beginning of year	271,779	252,157
Fund balances, end of year	$ 269,767	$ 271,779

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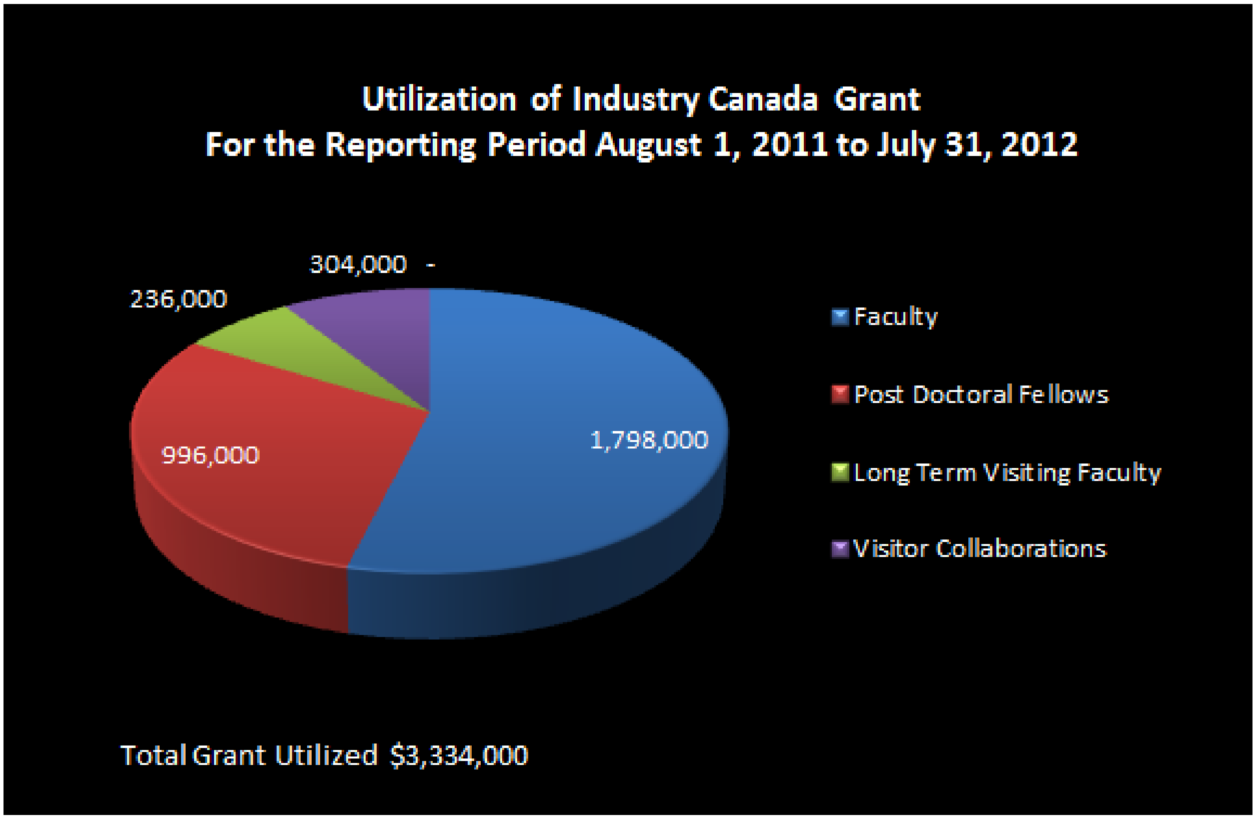
Expenditure of Industry Canada Grant



Performance Measurement Strategy

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

Performance Monitoring – Internal

- Annual reports on research activity submitted to the Director by all faculty and associate faculty members for evaluation
- Annual 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 researcher mentorship program
- Visitor research activity reports and ongoing tracking of all output
- Monitoring of postdoctoral researchers' post-Perimeter placement success
- Monitoring of researchers' international presence and impact through collaborations and invitations to lecture
- Internal review and evaluation of all outreach programs and products

Performance Monitoring – External

- Regular reporting to the international Scientific Advisory Committee (SAC) with subsequent performance assessment and recommendations (see Appendix E for a list of SAC members)
- Review of all faculty hires, renewals, and promotions by the Scientific Advisory Committee
- 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, training, and outreach activities and, in keeping with individual grant requirements, receive ongoing updates, reports, and yearly audited financial statements as required to ensure value for money while remaining aware of the Institute's research productivity and outreach impact.

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

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

Governance

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

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

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

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

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 2012-13

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, 2012-13

Objective 1: To deliver world-class research discoveries

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

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

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

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

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

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

Objective 8: To engage in high impact outreach

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

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

Appendices

Note: Appendices reflect the Perimeter community as of July 31, 2012.

Appendix A: Faculty and Associate Faculty Members

Faculty

Neil Turok is the Director of Perimeter Institute for Theoretical Physics in Waterloo, Ontario, Canada. He earned his PhD at Imperial College, London, in 1983, after which he held a postdoctoral fellowship in Santa Barbara. After his time in Santa Barbara he became 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. In 2009, he was named a Canadian Institute for Advanced Research (CIFAR) Fellow in the Cosmology and Gravity program. Professor Turok has worked in a number of areas of theoretical physics and cosmology, focusing on developing fundamental theories and new observational tests. Highlights of his research include showing how the polarization and temperature anisotropies of the cosmic background radiation would be correlated, developing a key test for the presence of the cosmological constant, formulating the Hawking-Turok instanton solutions describing the birth of inflationary universes, and advancing a cyclic model for cosmology, according to which the big bang is explained as a collision between two 'brane-worlds' in M-theory. Born in South Africa, Professor Turok founded the African Institute for Mathematical Sciences (AIMS) in Cape Town in 2003, a postgraduate educational centre that supports the development of mathematics and science across the African continent. For this work and his contributions to theoretical physics, he was awarded the TED Prize and a Most Innovative People award at the 2008 World Summit on Innovation and Entrepreneurship (WSIE). Professor Turok was also selected as the 2012 CBC Massey Lecturer.

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 to 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 in 2002 from Harvard University and, from 2002 to 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."

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

Laurent Freidel received his PhD from L'École Normale Supérieure 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.

Davide Gaiotto received his PhD from Princeton University in 2004 under the supervision of Leonardo Rastelli, was a postdoctoral fellow at Harvard from 2004 to 2007, and was a long-term Member at the Institute for Advanced Study in Princeton from 2007 to 2011. Gaiotto works in the area of strongly coupled quantum fields and has achieved several important conceptual advances, with potentially revolutionary implications. He was awarded the 2011 Gribov Medal of the European Physical Society.

Jaume Gomis received his PhD from Rutgers University in 1999, then worked 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. He has published over 40 papers, which 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), the 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 (2000-2001), 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 (now) 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 to 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 joined PI in 2010 as a junior Faculty member in the particle physics program. 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 to 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 and null results in terms of 'simplified models', making it easier to provide more robust theoretical interpretations of data. 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 he 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 joined PI in 2010 as a junior Faculty member in the particle physics program. She completed her PhD at Harvard in 2007 under the supervision of Nima Arkani-Hamed, a Distinguished Visiting 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.

Guifre Vidal joined PI as a senior Faculty member in May 2011 from the University of Queensland in Brisbane, where he was an Australian Research Council Federation Fellow and professor in the School of Mathematics and Physics. Dr. Vidal received his PhD in 1999 from the University of Barcelona, under the supervision of Professor Rolf Tarrach. He did three-year postdoctoral fellowships at the University of Innsbruck in Austria and the Institute for Quantum Information at Caltech before joining the University of Queensland. Dr. Vidal works at the interface of quantum information and condensed matter physics. He uses tensor networks to compute the ground state of quantum many-body systems on a lattice and to issue a classification of the possible phases of quantum matter or fixed points of the renormalization group flow. His past honours include a Marie Curie Fellowship, awarded by the European Union, and a Sherman Fairchild Foundation Fellowship.

Pedro Vieira 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 to 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.

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

Associate Faculty

Niayesh Afshordi (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 to 2007 and a Distinguished Research Fellow at Perimeter Institute from 2008 to 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.

Avery Broderick (jointly appointed with the University of Waterloo) joined Perimeter's faculty in September 2011. He completed his PhD at Caltech in 2004 and held postdoctoral positions at the Institute for Theory and Computation at the Harvard-Smithsonian Center for Astrophysics (2004-07) and the Canadian Institute for Theoretical Astrophysics (2007-11). Broderick is an astrophysicist with broad research interests, ranging from how stars form to the extreme physics in the vicinity of white dwarfs, neutron stars, and black holes. He has recently been part of an international effort to produce and interpret horizon-resolving images of a handful of supermassive black holes. With these, Broderick and his collaborators study how black holes accrete matter, launch the ultra-relativistic outflows observed, and probe the nature of gravity in their vicinity.

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, from 1999 to 2002 and a Research Fellow at the Michigan Center for Theoretical Physics, University of Michigan, from 2002 to 2003. He joined PI as an Associate Faculty member 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 to 1987, he was a Member in the School of Natural Sciences at the Institute for Advanced Study in Princeton, New Jersey, and from 1987 to 2005, he was a Faculty member at McGill University, where he was named 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, as well as numerous book and encyclopedia chapters, and has co-authored a graduate text on the Standard Model. From 2005 to 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.

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 to 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. His 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. From 1988 to 1990, he held a Killam postdoctoral fellowship at UBC and then a research fellowship at Peterhouse College, University of Cambridge. From 1992 to 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.

Sung-Sik Lee joined PI's faculty in July 2011 as an Associate Faculty member in theoretical condensed matter physics jointly appointed with McMaster University. Dr. Lee completed his PhD in 2000 at the Pohang University of Science and Technology (POSTECH) in South Korea, under the supervision of Professor Sung-Ho Suck Salk. He worked as a postdoctoral researcher at POSTECH, MIT, and the Kavli Institute for Theoretical Physics (Santa Barbara) before joining McMaster as an Assistant Professor in 2007. Dr. Lee's research focuses on strongly interacting quantum many-body systems using quantum field theory, as well as the intersections between condensed matter and high energy physics. His recent work has included, among other things, using gauge theory as a lens through which to examine the phenomenon of fractionalization, efforts to apply the AdS/CFT correspondence from string theory to quantum chromodynamics and condensed matter, and building a non-perturbative approach to understanding unconventional metallic states of matter.

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 to 2006, before becoming an Associate Professor there from 2006 to 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 to 2002 and a CITA National Fellow in 2001-2002. He was a Sloan Research Fellow from 2003 to 2005 and is currently a fellow of CIFAR, the Institute of Physics, and the APS. He is also an editorial Board member of *Classical and Quantum Gravity* and *Papers in Physics*.

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. 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 also been a Fellow of the Canadian Institute for Advanced Research (CIFAR) since 2010.

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.

Itay Yavin (jointly appointed with McMaster University) joined Perimeter as an Associate Faculty member in particle physics in 2011, with a joint appointment at McMaster University. Dr. Yavin completed his PhD in 2006 at Harvard University under the supervision of PI Distinguished Visiting Research Chair Nima Arkani-Hamed. After completing his PhD, he joined the Department of Physics at Princeton University as a Research Associate from 2006 to 2009. Prior to coming to PI, Dr. Yavin was a James Arthur Postdoctoral Fellow at the Department of Physics at New York University. Dr. Yavin's research focuses on particle physics and the search for physics beyond the Standard Model. In particular, he is interested in the origin of electroweak symmetry breaking and the nature of dark matter. Most recently, he has worked on interpreting puzzling data coming from experiments looking for dark matter in the lab.

Appendix B: Distinguished Visiting Research Chairs

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

Yakir Aharonov is a professor of theoretical condensed matter physics at Chapman University and Professor Emeritus at Tel Aviv University, 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 lecturer for the Perimeter Scholars International master's program. Professor Arkani-Hamed has developed theories on emergent extra dimensions, 'little Higgs theories', and recently proposed new models that can be tested using the Large Hadron Collider (LHC) at CERN in Switzerland. In 2012, he was one of the inaugural winners of the Fundamental Physics Prize.

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

Ganapathy Baskaran is an Emeritus Professor at the Institute of Mathematical Sciences, Chennai in India, where he recently founded the Quantum Science Centre. He has made important contributions to the field of strongly correlated quantum matter. His primary research focus is novel emergent quantum phenomena in matter, including biological ones. He is well known for his contributions to the theory of high temperature superconductivity and for discovering emergent gauge fields in strongly correlated electron systems. He predicted p-wave superconductivity in Sr_2RuO_4, a system believed to support Majorana fermion mode, which is a popular qubit for topological quantum computation. In recent work, he predicted room temperature superconductivity in optimally doped graphene. From 1976 to 2006, Dr. Baskaran contributed substantially to the Abdus Salam International Centre for Theoretical Physics in Trieste, Italy. He is a past recipient of the S. S. Bhatnagar Award from the Indian Council of Scientific and Industrial Research (1990), the Alfred Kasler ICTP Prize (1983), Fellowships of the Indian Academy of Sciences (1988), the Indian National Science Academy (1991) and the Third World Academy of Sciences (2008), and the Distinguished Alumni Award of the Indian Institute of Science, Bangalore (2008).

Juan Ignacio Cirac, Director of the Theory Division of the Max Planck Institute of Quantum Optics in Germany, is a leading quantum information theorist whose group 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.

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

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 honorary degrees, was made a Companion of the British Empire in 1982, and was made a Companion of Honour in 1989. He is the recipient of many awards, medals, and prizes, and is a Fellow of The Royal Society and a Member of the US National Academy of Sciences.

Patrick Hayden 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 Sloan Research 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 to 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 a lecturer for Perimeter Scholars International.

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

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

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

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

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

Paul Steinhardt is the Albert Einstein Professor in Science and Director of the Princeton Center for Theoretical Science at Princeton University. Dr. Steinhardt is a Fellow in the American Physical Society (APS) and a member of the National Academy of Sciences. He shared the P.A.M. Dirac Medal from the International Centre for Theoretical Physics for the development of the inflationary model of the universe, and the Oliver E. Buckley Prize of the APS for his contributions to the theory of quasicrystals. His research interests include particle physics, astrophysics, cosmology, and condensed matter physics. Recently, with Neil Turok, he has developed a cyclic model for cosmology, according to which the big bang is explained as a collision between two ‘brane-worlds’ in M-theory. In addition to his continued research on inflationary and cyclic cosmology, Steinhardt has been one of the developers of a new class of disordered ‘hyperuniform’ photonic materials with complete bandgaps, and he conducted a systematic search for natural quasicrystals that has culminated in discovering the first known example. He is currently organizing an expedition to Far Eastern Russia to find more samples and study the local geology where they are found.

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

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

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

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

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

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

Appendix C: Affiliate Members

Name	Institution	Research Area
Ian Affleck	University of British Columbia	Condensed Matter
Arif Babul	University of Victoria	Cosmology
Leslie Ballentine	Simon Fraser University	Quantum Foundations
Richard Bond	University of Toronto/CITA	Cosmology
Ivan Booth	Memorial University	General Relativity
Vincent Bouchard	University of Alberta	Quantum Fields and Strings
Robert Brandenberger	McGill University	Cosmology
Gilles Brassard	University of Montreal	Quantum Information
Anne Broadbent	University of Waterloo/IQC	Quantum Information
Anton Burkov	University of Waterloo	Condensed Matter
Bruce Campbell	Carleton University	Particle Physics
Benoit Charbonneau	St. Jerome's University	Gauge Theory
Jeffrey Chen	University of Waterloo	Condensed Matter
Andrew Childs	University of Waterloo/IQC	Quantum Information
Matthew Choptuik	University of British Columbia	Numerical General Relativity
Dan Christensen	Western University	Quantum Gravity
Aashish Clerk	McGill University	Condensed Matter
James 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

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

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

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

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

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

Appendix D: Board of Directors

Mike Lazaridis, **O.C., O.Ont., Chair**, is Founder, Board Vice-Chair, and Chair of the Innovation Committee of Research In Motion Limited (RIM). A visionary, innovator, and engineer of extraordinary talent, he transformed the communications industry with the development of the BlackBerry. He is the recipient of many technology and business awards, a Fellow of the Royal Society of Canada, and a recipient of both the Order of Ontario and the Order of Canada.

Cosimo Fiorenza, **Vice Chair**, is the Vice-President and General Counsel of the Infinite Potential Group. 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 the former Chairman & Chief Executive Officer of Scotiabank, from which he retired in March 2004. He holds a BSc in Mathematics and Physics from the University of Toronto, an MBA from the Harvard Business School, and is a C.A. and a Fellow of the Institute of Chartered Accountants of Ontario. Mr. Godsoe remains active through a wide range of corporate boards and non-profit directorships.

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

Steve MacLean 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 he has participated in missions on the Space Shuttles Columbia (1992) and Atlantis (2006) to the International Space Station. In addition to senior roles within the CSA and extensive experience with NASA and the International Space Station, he is a strong supporter of science literacy and child education.

Art McDonald has been the Director of the Sudbury Neutrino Observatory (SNO) for over 20 years. He holds the Gordon and Patricia Gray Chair in Particle Astrophysics at Queen's University and works on the SNO+ experiment at the international SNOLAB, researching an accurate measurement of neutrino mass and helping to explain the processes that generate matter in the early universe. McDonald has received numerous awards for his research, including the 2011 Henry Marshall Tory Medal from the Royal Society of Canada and the 2007 Benjamin Franklin Medal in Physics, alongside researcher Yoji Totsuka. He was named an Officer of the Order of Canada in 2007.

Barbara Palk recently retired as President of TD Asset Management Inc., one of Canada's leading money management firms, and as Senior Vice President of TD Bank Financial Group. She is a Fellow of the

Canadian Securities Institute, a CFA Charterholder, and a member of the Toronto Society of Financial Analysts. Ms. Palk is Vice-Chair of the Board of Trustees of Queen's University and the Chair of its Investment Committee, and a member of the Boards of the Shaw Festival and Greenwood College School. She is a recipient of the Ontario Volunteer Award and was honoured by the Women's Executive Network in 2004 as one of Canada's Most Powerful Women: Top 100 in the Trailblazer category.

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

Appendix E: Scientific Advisory Committee

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

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

Matthew Fisher, Kavli Institute for Theoretical Physics (2009-Present)
Professor Fisher is a condensed matter theorist whose research has focused on strongly correlated systems, especially low dimensional systems, Mott insulators, quantum magnetism and the quantum Hall effect. He received the Alan T. Waterman Award from the National Science Foundation in 1995 and the National Academy of Sciences Award for Initiatives in Research in 1997. He was elected as a Member of the American Academy of Arts and Sciences in 2003 and to the National Academy in 2012. Professor Fisher has over 150 publications.

Brian Greene, Columbia University (2010-Present)
Professor Greene is a Professor of Mathematics and Physics at Columbia University, where he is co-Director of the Institute for Strings, Cosmology, and Astroparticle Physics (ISCAP). Professor Greene has made 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.

Erik Peter Verlinde, University of Amsterdam (2010-Present)
Professor 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, including Verlinde algebra and the Verlinde formula, which are important in conformal field theory and topological field theory. His research centres on string theory, gravity, 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 (2010-Present)
Professor Whaley is a Professor in the Department of Chemistry at the University of California, Berkeley, where she is Director of the Berkeley Quantum Information and Computation Center. Professor Whaley's research centres on understanding and manipulating quantum dynamics of atoms, molecules, and nanomaterials in complex environments to explore fundamental issues in quantum behaviour. She has made major contributions to the analysis and control of decoherence and universality in quantum information processing, as well as to analysis of physical implementations of quantum computation. Professor Whaley is also known for her theory of molecular solvation in nanoscale superfluid helium systems. Current research includes theoretical aspects of quantum information science, quantum simulation of exotic topological phases, and exploration of quantum effects in biological systems.

Appendix F: Media Highlights

In 2011-12, Perimeter Institute received major coverage in both national and international media, including *The Globe and Mail*, *National Post*, *Toronto Star*, *Macleans*, *CTV*, *CBC*, *NBC*, *Wall Street Journal*, *Australian Herald*, *Nature*, *Science*, *National Geographic News*, *Der Spiegel*, and *The Economist*, among others. Some highlights are included below.

Outlet	Headline	Date	Summary
Grand Opening Related			
Globe and Mail	A playhouse to foster future Einsteins in Waterloo	Sept. 17, 2011	This 2-page, full-colour photo spread featured several aspects of the new expansion that facilitate basic research and discovery. This feature appeared on pages A12-13 in the Saturday Globe.
Globe and Mail	Perimeter lures star theoretical physicist away from MIT	Sept. 17, 2011	This story accompanied the photo spread above, announcing the appointment of Dr. Xiao-Gang Wen.
National Post	The buzz factory	Sept. 17, 2011	This article discussed the new expansion, featuring a very personal interview with Latham Boyle. It appeared on the front page, below the fold in the Saturday edition.
Waterloo Record	• Seeking rippled in space-time; • The next computer revolution; • On the dark side of the universe	Sept. 17, 2011	This 2-page spread featured the work of 4 researchers at PI, discussing the practical applications of their theoretical research. Full-colour photos accompanied the articles. It appeared in pages A6-7 in the Saturday edition.
CTVNews.ca	Ontario physics institute grabbing top scientists	Sept. 25, 2011	Featured with a photo gallery of over 40 images, this article shares the hype of science celebrities at the grand opening.
The Economist	Stretching the perimeter	Sept. 29, 2011	This article on PI and the new expansion are part of a larger feature on “the future of physics.”
Relating to ‘faster-than light neutrinos’ discovery			
Waterloo Record	Physicists cautious about reports of faster-than-light neutrinos	Sept. 25, 2011	This article emphasizes the caution required when reacting to the potential findings at CERN. Cliff Burgess, PI researcher, is interviewed and was quoted as saying, “For spectacular things, you have to have spectacular evidence.”

AAAS op-ed			
Globe and Mail	Great science opens doors to the future	February 15, 2012	Neil Turok writes about the extraordinary power of science and education in advance of the AAAS Annual Meeting
Waterloo Region Innovation			
The Walrus	The Invention of Waterloo	December 8, 2011	The Walrus' Don Gillmour dives into the history of Waterloo and how it grew into one of Canada's leading hubs for innovation. Special mention is made of Mike Lazaridis' founding of Perimeter.
Research related			
Nature	Physicists hunt for dark forces	April 3, 2012	This article explores the results coming from experiments at various particle colliders. Perimeter's Philip Schuster was interviewed.
Science Daily, PhysOrg, Yahoo India, Australian Herald, Space Daily	NASA's WMAP satellite finds no evidence for 'knots' in space	June 13, 2012	A new study published in Physical Review Letters, involving Perimeter Postdoctoral Researcher Matt Johnson, received a lot of online attention after claiming to find no 'cosmic textures' (imperfections in the structure of space theorized to exist from Big Bang)
Relating to the Higgs Boson discovery			
Macleans	Why the Higgs boson discovery changes everything	July 17, 2012	Macleans' Kate Lunau and Katie Engelhart wrote about the recent Higgs discovery, exploring what it was like at CERN during the announcement and what impacts the discovery could have for the future. Neil Turok is quoted.
Toronto Star	Much ado about nothing	July 8, 2012	Perimeter Associate Faculty Cliff Burgess writes an op-ed for the Toronto Star tied to the Higgs. Burgess notes that "far-sighted investments in scientific research can pay off in unpredictable ways."

THE GLOBE AND MAIL

A playhouse designed to foster future Einsteins in Waterloo

Written by: Anne McIlroy

Date: September 17, 2011

With the opening of the Stephen Hawking Centre, Waterloo's world class research facility doubles its size

It looks like a spaceship, feels like a playhouse and is designed to inspire researchers as they tackle some of the hardest problems in science.

The Stephen Hawking Centre, a 55,000-square-foot expansion to the Perimeter Institute for Theoretical Physics in Waterloo, Ont., officially opens this weekend - a bold bet that a building can nurture genius, promote unconventional thinking and foster the kind of collaboration essential for success in many scientific fields.

"I know how important an inspirational environment is to get people excited and motivated to think about these most difficult, abstract theoretical ideas, like what happened at the Big Bang, what goes on inside a black hole and conceptualizing the way fundamental physics works," says Neil Turok, director of the institute. So, he set a simple but lofty goal for Teeple Architects Inc., the firm chosen to design the expansion.

"We asked them to provide the optimal environment for the human mind to conceive of the universe."

What, exactly, does that kind of environment look like?

Natural light, good ventilation and a connection to the outside world are important for learning and thinking, says architect Stephen Teeple. To that end, the offices have large windows that look out onto a lake and there is a herb garden in the middle of the building.

A lot of thought also went into little things that would bring people together, he says. Bridges and staircases provide many different routes to a destination - be it a washroom, or the bistro on the ground floor. Three "interaction areas," adjacent to hallways, offer places to stop, chat and, if need be, scrawl equations on blackboards or glass boards.

Perimeter was created in 1999, by Research in Motion co-chief executive officer Michael Lazaridis, as an independent centre devoted to the study of fundamental questions in physics. The celebration to mark the opening of the new addition comes at a troubled time for RIM: The stock price fell 20 per cent Friday after second quarter results fell short of expectations.

The $29-million expansion was funded with a mix of private and public money, and doubles the size of the institute. At capacity, it will be the largest centre of its kind in the world, with room for 250 researchers.

The older part of building, completed in 2004, has more of an atmosphere of quiet contemplation. The addition has a younger, more playful spirit.

"The people here are working on such difficult, often frustrating problems, doing long calculations. . . . One of the biggest problems is to keep them happy and motivated and feeling positive," says Dr. Turok. "To change it from a 'grindstone' environment to a playhouse is actually key."

http://www.theglobeandmail.com/news/technology/science/hawking-centre-opens-to-foster-future-einsteins-in-waterloo/article2169734/

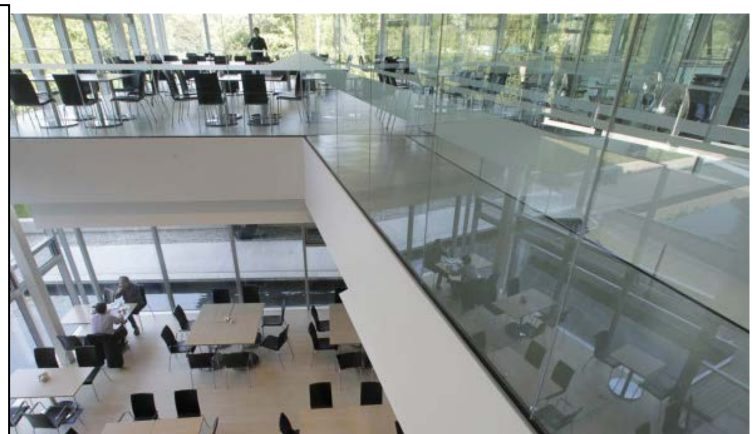
http://www.theglobeandmail.com/news/technology/science/a-look-inside-the-hawking-centre/article2169481/?from=2169734

The Time Room

Blackboards warp around the sloping lecture theatre where some of the biggest names in theoretical physics will teach students in the master's program. "We believe you learn better from a three-dimensional representation," says Dr. Turok. It's also designed for collaborative learning – swivelling chairs allow the students, who come from 18 different countries, to solve problems together. The lecture hall is connected to a common room, where there isn't a cubicle in sight; instead there are sofas, comfortable chairs and blackboards. "They don't go off and sit in [cubicles]. This is not the way we want people to learn," says Dr. Turok.

The Bistro

The Black Hole Bistro, which had been on the fourth floor, was moved to the ground level in the new addition. "One of the first things Neil said to us is he wanted scientists to interact from the moment they walked in the door," says Mr. Teeple. The Black Hole Bistro is one of the main places where the researchers run into not only each other, but visiting scholars. "People come in and have a coffee and sit at a table and maybe even never get to their offices," says Dr. Turok.



Interaction areas

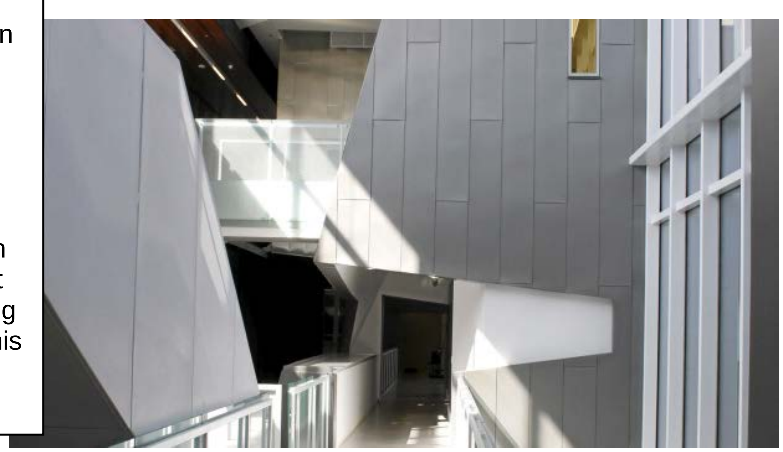
These exist on half levels in between the main floors, as well as on the fourth floor. The space measures about nine metres by 4.5 metres, with blackboards or glass boards to scratch down ideas. They are designed to be welcoming spaces where people with offices on different floors can meet to talk, or where two researchers who bump into each other can shift from a casual chat to a deep discussion. They were put at half levels so the sounds of brainstorming sessions or impromptu debates won't travel to the offices on the second and third floors.

The Sky Room

This was designed as an internal discussion area where colleagues can comfortably share their wildest ideas. "In many ways, the most interesting ideas that come out of an institute are the ones that have time to gestate within a closed community of researchers. People can be bold, and share their ideas with colleagues long before they are ready to share them with the outside world," says Dr. Turok. It was designed to feel fun and free, like a "rec room in the sky," says Mr. Teeple, hence the red carpet, large windows and funky furniture. "If you were in music, it is the place where you would go and invent your songs."

Angles and alternate routes

There are different routes to get to any point in the building, a feature intended to promote accidental interactions. The new wing has angles everywhere and almost no parallel lines, Dr. Turok says, which like many other unconventional elements in the architecture are intended to inspire the sense that traditional approaches have to be changed. In the 20th century, architect Frank Lloyd Wright broke established paradigms to create working environments that were inspirational. "I see this building in exactly that spirit, except for the 21st century," says Dr. Turok.



THE GLOBE AND MAIL

Perimeter Institute lures star theoretical physicist from MIT to Waterloo

Written by: James Bradshaw

Date: September 17, 2011

Xiao-Gang Wen unveiled as inaugural Isaac Newton Chair with $8-million endowment

The Perimeter Institute has scored a coup in luring world-renowned theoretical physicist Xiao-Gang Wen away from the Massachusetts Institute of Technology.

Formerly of MIT, Xiao-Gang Wen, is the new Isaac Newton Chair in theoretical physics, at the Perimeter Institute for Theoretical Physics in Waterloo. He poses at the instate on September 16, 2011.

Professor Wen was announced Friday as the inaugural BMO Financial Group Isaac Newton Chair in Theoretical Physics, now the world's best-endowed chair in the field at $8-million, and intended to be the first of five named after the discipline's founding fathers.

At 49, the Chinese-born Prof. Wen is a star of condensed matter theory, having played key roles in several groundbreaking shifts in the way scientists understand matter and materials.

Prof. Wen found the Perimeter Institute immediately alluring when he first visited in 2004. The institute's focus on fostering interaction between researchers threw him into new intellectual territory, a space for merging ideas with common threads as well as radical differences.

"Suddenly, you're seeing things in a different dimension. It's kind of a mind-opening experience for me," Prof. Wen said.

He is already a familiar figure at Perimeter, having held a distinguished visiting chair for the past three years, but will now arrive full-time to build a new research team.

A $4-million donation from BMO and matching funds from Perimeter's endowment established the Newton Chair last fall - the bank's largest ever donation to science, and the biggest private gift to Perimeter. Traditionally, fundamental physics has struggled to compete with more practical sciences for high-level support.

"If it has a name, it's not new," Prof. Wen said. "How do you [convince someone to] support something that doesn't even have a name?"

But discoveries in theoretical physics have driven huge practical innovations in fields like computing and electronics, making Prof. Wen a smart investment for "the future of commerce" in Canada, according to BMO president and CEO Bill Downe.

"What I do actually is material, it's just new kinds of materials," Prof. Wen said. "I'm expanding the toolbox."

http://www.theglobeandmail.com/news/technology/science/perimeter-institute-lures-star-theoretical-physicist-from-mit-to-waterloo/article2169753/

NATIONAL POST

The buzz factory

Alternative title online: Newly opened Hawking Centre aims to redefine physics

Written by: Joseph Brean

Date: September 17, 2011

A new addition is complete and the Perimeter Institute for Theoretical Physics (PI) is holding a Grand Opening of the Stephen Hawking Centre at Perimeter Institute Sept. 16, 17, 18th in Waterloo, Ontario

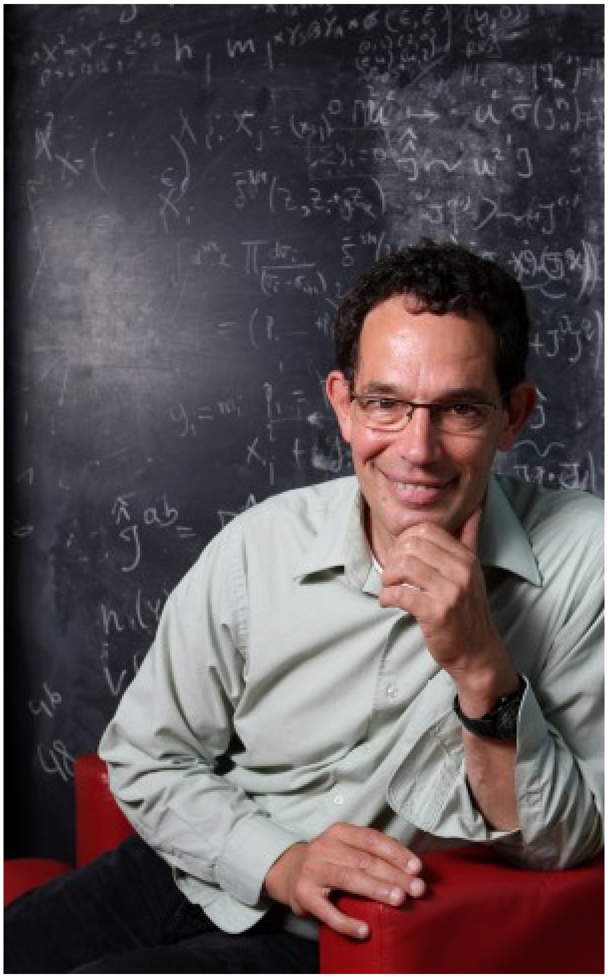
Leaning forward in a swivel chair, his boyish bowl-cut silhouetted against the floor-to-ceiling windows of his sparsely modern office, Latham Boyle, a cosmologist, suddenly stopped talking about cosmology. Behind him, a hawk settled into the gnarled upper branches of a tree outside the new Stephen Hawking Centre at the Perimeter Institute for Theoretical Physics, which has its ribbon cutting Saturday.

At first he seemed deep in thought, but in a moment it became wondrously obvious, as quaint as it was profound. This man was going to cry about theoretical physics.

"I'm a biological anomaly. I get weepy at inappropriate moments," he said, gathering himself, but failing to wipe the rapture from his face. "The laws of nature are turning out to be miraculous, much more beautiful than you had any right to expect, symmetrical, economical. They could have turned out to be like the tax code. Nobody knows why they didn't turn out to be messy laws. I don't think people appreciate this fact about the universe."

Outside in the hallway, open to the soaring atrium in which workers fussed over last minute details, all kinds of theoretical physicists passed by, stepping over drop cloths and toolboxes on their way to lunch in the stylish Black Hole Café, while others lounged with books in the airy Sky Room, and still others played ping pong. This is the point of Perimeter, to give deep thinkers like Mr. Boyle a quiet place for near-mystical reflection on foundational questions, but also to surround them with others who share those lofty dreams and abilities, and are eager to chat over a cappuccino.

“There’s something crazy going on, and everyone wants to figure it out,” Mr. Boyle said of his colleagues.



Neil Turok, Institute Director of the Perimeter Institute for Theoretical Physics.

Physics does funny things to the people who study it, and few have thought more strategically about how to harness this quasi-religious devotional aspect than the man in the office at the end of the hall, Neil Turok, Perimeter’s director for the last three of its 10-year history. In that time, by luring young stars such as Mr. Boyle and Nobel-grade eminences such as Stephen Hawking, and setting them up in this comfortable building alongside an art gallery on the shore of a little lake in Waterloo, Ont., he has nurtured a culture of research that is at odds with stuffy academic traditions and closer to that of a tech start-up — neither Google nor Princeton, but a bit of both.

The Hawking Centre, named for Mr. Turok’s former Cambridge collaborator, who now holds one of Perimeter’s distinguished research chairs, is the latest expression of this vision, and will house PI’s new international master’s program. It also marks Perimeter’s coming of age. Once a saucy start-up with big plans, it is now a realized vision that must live up to its own hype. From its origins in an old post office, through years of planning and construction, the place has been designed to foster buzz, that ineffable quality that propels a good idea toward popularity.

“You’ve got to create the vibe in the institution. And it’s a very subtle thing. You cannot legislate it,” Mr. Turok said.

From attracting researchers to evaluating their theories and sharing them with the world, buzz is crucial to high science. It is hard to imagine Albert Einstein, the first celebrity physicist, without the wild hair, or Hawking without the wheelchair, or even Isaac Newton without the apple. Modern physics is in thrall to the buzz of big ideas, and desperate for a new one. Newton explained the movement of the heavens with gravity. James Clerk Maxwell showed electricity and magnetism are the same thing. Einstein did the same for space and time. Now, it is Dark Matter, Dark Energy and the God Particle that generate all the buzz. They fill gaps in theory, explain weird observations, and countless millions are being spent on their detection. But unlike the revolutions of Newton or Einstein, these newer ideas have not yet yielded real-world evidence. At least one senior Perimeter scientist thinks they never will, because they are simply false. And so the next big idea, if it solves these problems, will be bigger than we can now imagine, and it will ride on a wave of buzz.

That is Perimeter's goal, Mr. Turok said. He does not want to make incremental contributions to physics journals and academic conferences. He wants to re-invent the field, and he wants everyone to know about it, amateur and expert alike. The ultimate value of Perimeter, he said, will not depend on its fancy new building, nor its rich program of educational outreach, its jazz recitals, art shows or pub nights. It will be judged on a single idea, as yet unthought, by a single person. It might take a decade or more, but this is the mission. Perimeter is all in for a big bet.

"Nobody's ever given $100-million to theoretical physics. It's completely unprecedented. And then the government matched it. Wow," Mr. Turok said, referring to RIM co-founder Mike Lazaridis' foundational donation. "This is the largest strategic investment in theoretical physics, which is the most foundational subject in science. The challenge for us at PI is to live up to the opportunity. We have to create the optimal environment for the human mind to understand the universe."

"Most people around the world have assumed that theoretical physics is such a hard field and such a foundational field that you cannot plan strategically for it. It just wasn't possible. You had to just hope that somewhere in the middle of Bangladesh in a small, unknown university was an utterly brilliant person who would revolutionize everything. So my point of view is that's not the way the world works. I mean, when you want to do something, you declare, you set about doing it systematically. Think about Kennedy and the Moon," Mr. Turok said. "With theoretical physics, it's more delicate than innovation. We're talking about ideas. How do you speed up someone having an idea?"

"Maybe that's impossible," he adds, but he does not mean it. He thinks he is already doing it. He proudly declares, for example, that he just won a recruitment battle with Stanford.

Dr. Hawking himself, who is hosting Saturday's grand opening via video-link, has described the vibe at Perimeter as being on a historical par with Einstein's Berlin of the 1920s, or Cambridge in the 1960s when Hawking's own work on black holes illuminated the origins of the universe. A recent audit by KPMG for Industry Canada was similarly full of praise, citing Perimeter's "transformative" impact on theoretical physics in Canada, which is now a "visible and respected world player."

"There are not many areas in which PI could look at opportunities for improvement. By far the most common complaint [in a global survey of eminent physicists] was the geographical location of the Institute, and this is obviously not something PI has control over," it said.

Mr. Boyle, who was preparing his report to PI's scientific advisory committee, highlighted some of the work he thinks could be transformative. Researcher Matthew Johnson, for example, has published work on the theory that our universe is but a single bubble in the fizz of a larger "multiverse." If this is so, then there might be places where the bubbles have bumped into each other, and if you know what to look for — a circular imprint on the cosmic background radiation, often called the "flash" of the big bang — you might see evidence of this. Mr. Johnson's contribution was to describe the probability of what such a cosmic "bruise" might look like. Proof remains elusive, but it is hard to imagine an idea with better buzz potential than that our universe is not alone.

"You have to be sufficiently in love with your theory in order to pursue it, but if you're too in love with them, you won't see that they are wrong, which they usually are," Mr. Boyle said.

To follow this romantic analogy, senior researcher John Moffat is a divorce lawyer, mopping up after love gone bad. With his dogged criticism of common wisdom in physics, he styles himself as the ultimate buzzkill, the aged, skeptical sage to Mr. Boyle's youthful idealist. For example, he has invented a new theory of gravity that does not require the strange, unproven concepts of Dark Energy and Dark Matter.

His skepticism is most acute, however, in his thoughts on the God Particle, otherwise known as the Higgs boson, which was proposed almost 50 years ago as the final piece of the Standard Model of particle physics. In essence, the Higgs is a hypothesis for why all the other particles have mass. It is called a particle, but usually exists as a wave, and when other particles pass through it, the Higgs slows them down like a fly in honey. To find it, though, scientists must create the actual particle, and the only way to do that is to slam a bunch of other particles together at extremely high speeds.

As a theory with buzz, the God Particle is hard to beat, and not just because of the catchy nickname. It inspired the construction of the Large Hadron Collider on the Swiss-French border, the world's biggest particle accelerator, and the careers of a generation of physicists depend on its discovery, which has seemed imminent since the LHC was switched on last year. But it has not happened yet, and as Mr. Moffat puts it, the "window is closing."

"There's a depression setting in. They can't see it," Mr. Moffat said. "They're gearing up for the statement that there is no Higgs… It's becoming quite serious. This god has clay feet."

The death of the God Particle would be a big blow to buzz, and the impact would be measured in political and financial support for future big experiments. But it would be an opportunity for Perimeter to realize its goal of guiding future experimenters toward real, era-defining discovery. Fail, and Perimeter will still be a neat place to learn and teach. Succeed, and $100-million will seem like a bargain.

http://news.nationalpost.com/2011/09/17/newly-opened-hawking-centre-aims-big-attemps-to-redefine-physics/#more-94934

WATERLOO REGION
RECORD

Ready to reshape how we understand reality

Written by: Rose Simone

Date: September 17, 2011

WATERLOO — Neil Turok has a futuristic dream, one that features Waterloo going down in history as the place that opened up a new chapter for 21st century physics and technology.

"If we focus, we could come up with the discoveries that will redefine the future," says Turok, director at the Perimeter Institute for Theoretical Physics, which is opening up its brand new Stephen Hawking Centre addition this weekend.

Perimeter Institute director Neil Turok believes that the discoveries made at the Waterloo research centre have the potential to redefine the future.

It sounds grandiose to think the Perimeter can go up against world-renowned institutions such as Princeton or Cambridge in this endeavour.

But Turok points to how much has been accomplished at the young institute since it was launched just 11 years ago by Mike Lazaridis, the Research In Motion co-founder who put in $100 million of his own money to get it started.

It likely was largest private donation in Canadian history.

The Perimeter opened with an initial complement of 10 to 15 resident researchers in the old post office building on King Street in downtown Waterloo. In 2004, it moved into a 65,000-

square-foot building on Caroline Street. The building caused a stir because of its unusual pitch-black, angular facade design.

Now, with the help of provincial and federal governments as well as private donations, the new $29 million Stephen Hawking Centre adds 55,000 square feet of space.

With that extra room, the Perimeter hopes to boost its present complement of about 100 physicists to 250 over the next few years.

By the standards of theoretical physics institutes around the world, that's big.

"This will easily be the biggest in the world," Turok says. "In many ways, something of this scale is unique in history."

Wrapping around Waterloo's Perimeter Institute, the new Stephen Hawking Centre will almost double the size of the world-leading theoretical physics research centre.

The idea is to put the best minds from around the world together in order to speed up discoveries in fundamental physics, Turok says. There is no guarantee such a deliberate effort will work, "but my sense is that it will," he says.

Turok, who came from Cambridge University to take the job as director in 2008, remembers telling his colleague Stephen Hawking about this institute in Canada with a mission to study quantum theory and space-time — two of the Holy Grails of physics.

Hawking's eyes "just lit right up," Turok says.

Hawking, who advanced the understanding of black holes and is easily the most famous physicist of the modern era, lent both his name and his time to the institute. Despite his long struggle with a motor-neuron disease that has left him severely paralyzed, he was in Waterloo as a distinguished research chair for two months last year.

“For him to come here, form an impression, meet the researchers and discuss scientific ideas is definitely a sign that we are taken very seriously by one of the leading authorities in the world,” Turok says.

Hawking will not be in Waterloo for the grand opening of the centre, but arrangements have been made for him to take part in the celebrations by video. Scientists, historians and communicators have been invited to talk about the impact Hawking has had, not just in physics but in inspiring people to achieve their potential regardless of what obstacles they face.

The new centre, designed by Teeple Architects Inc. of Toronto, wraps around the four levels of the existing building in a space-shuttle-like design. At every half level, there are open hubs for discussion and interaction.

Along with new offices, there are seminar and workshop rooms and a new bistro area. Sophisticated audiovisual and information technology equipment will allow visualization and analysis of complex calculations, and real-time collaboration with colleagues from around the world.

The institute prides itself not just on research, but also explaining it.

Greg Dick, director of educational outreach at the Perimeter, says demand for the monthly public lectures in a Waterloo high school gym is so strong the more than 600 free tickets are snapped up in minutes.

“There is a real thirst for science in this community,” he says.

He says the Perimeter’s outreach goal is not just to the local community, but to all of Canada and the world.

“We want Canada to have the most scientifically literate population in the world.”

Besides public lectures and physics festivals, the institute runs teacher workshops and is supporting the creation of a national network of physics teachers. It has educational tools online and in the form of kits that can be used in classrooms.

Dick says the institute is working with all the provinces to make sure modern physics gets into the school curriculum everywhere. There are also summer programs to bring bright young people from around the world to the institute to meet scientists.

Perimeter Scholars International, meanwhile, is a year-long program for top university students who are thinking of pursuing graduate studies in physics.

All of that helped to spread the word about the Perimeter.

But Turok knows the institute’s reputation ultimately depends on the science that happens there.

“If your ideas are wrong, that is going to be found out very quickly,” he says.

The institute has made a name for itself in everything from the study of fundamental particles and forces of nature, to the study of black holes — regions of space-time where gravity is so dense that not even light can escape.

Some of the physicists at the Perimeter are working to help make sense of the spray of particles that come out when protons are smashed together inside the Large Hadron Collider, located in a 27-kilometre tunnel deep underground near Geneva, Switzerland.

“That’s a one-billion-euro per year ($1.4-billion Cnd) project and it is the greatest experiment of all time,” Turok says. “Perimeter researchers are in a key position, trying to make sense of what they see.”

Others are involved in the theoretical side of other big experiments, such as the Laser Interferometer Gravitational-Wave Observatory. It's housed in two huge structures in the United States; and is looking for ripples in the fabric of space-time.

There is also work on quantum information, which dovetails nicely with research being done at the University of Waterloo's Institute for Quantum Computing and elsewhere around the world where people are working on quantum computers.

Turok is hiring people with expertise in condensed matter physics in order to build a strong team in Waterloo to help foster the development of novel quantum materials with unusual properties.

"I believe that Waterloo could become the centre of 21st century quantum electronics," he says. "That fits with what the Institute for Quantum Computing is doing. It fits with what the technology community here is doing. If we do this right, I think we might not only develop the theory for the experiments, but also the spinoff into industry."

The Perimeter has a strong endowment fund, totalling more than $200 million. Turok wants to grow it to $400 million in order to provide the institute with a stable, sustainable source of funding for the long term.

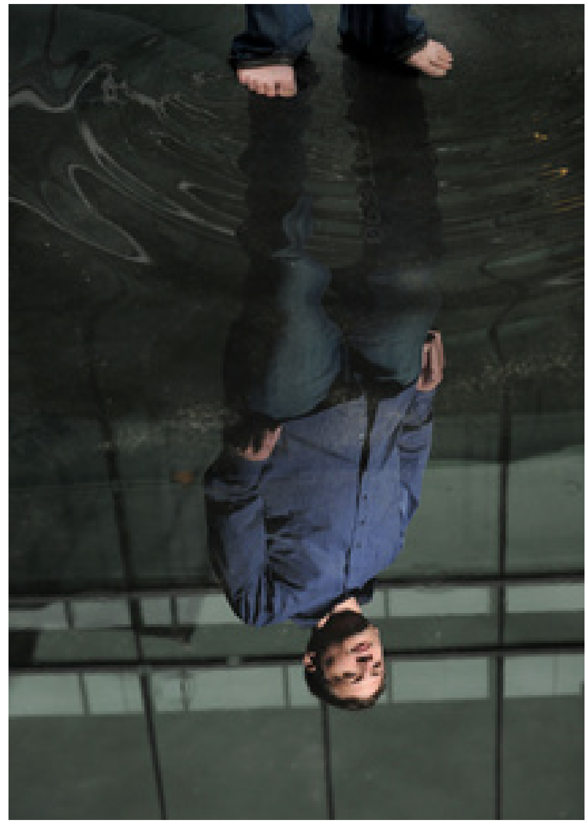
"We want to make this into a jewel that will last," Turok says. "The world will continue to need breakthroughs in theoretical physics for many reasons — for energy, for communications, for all the areas where physics has made breakthroughs in the past."

The Perimeter is young and has freedom to move quickly, Turok says. "It is very exciting. We have been given good resources, fantastic support, and now, we have to show it is working."

http://www.therecord.com/news/business/article/595910--perimeter-institute-set-to-revolutionize-the-21st-century

WATERLOO REGION
RECORD

Seeking ripples in space-time



Written by: Rose Simone

Date: September 17, 2011

WATERLOO — Millions of years ago, when dinosaurs first roamed the earth, there were acts of violence in galaxies far, far away.

There would have been interstellar smack-ups of gigantic proportions in the merger of two black holes — strange entities so heavy they could pack something many times the mass of the sun into a space the size of Waterloo, with gravity so intense not even light could escape its grip.

Or perhaps two neutron stars, each so dense that a teaspoonful of star material weighs billions of tons, spiralled into each other, in a massive, explosive crash.

Such collisions would have shaken the fabric of space-time itself, creating “ripples in space-time,” or gravitational waves. Some of those were destined to someday reach the Earth.

Chad Hanna Chad Hanna stands in the reflecting pool at the Perimeter Institute, where he is involved in the search for gravitational waves produced by massive violent events in the universe.

Fast forward to today. In Livingston, La., and Hanford, Wash., two unusual giant L-shaped structures have been built; they are vacuum tubes with arms extending out about four kilometres into the landscape. These huge scientific instruments comprise the Laser Interferometer Gravitational-Wave Observatory. They are designed to detect those ripples in the fabric of space-time that happened many millions of years ago.

When that happens, maybe after the observatory instruments have been fully upgraded in 2015, Chad Hanna, a researcher at the Perimeter Institute for Theoretical Physics in Waterloo, will pour over the data.

“A lot of what I do is very computational,” he says. “We have to look at the data stream and separate out all the garbage in that data to look for genuine signals,” he adds.

Hanna is especially interested in figuring out what signals would announce the merger of two black holes.

If the ripples in space-time pass through the Earth, they should generate tiny distortions in the laser light measurement of the long arms at these two sites in the United States. If the same distortion happens at both sites at the same time, physicists can be confident they may have picked up evidence of an extraterrestrial event, not just some local regional phenomenon like a microearthquake.

But it's not easy, Hanna says. The distortions would be very tiny. "We know they are extremely weak. We know our instruments are just barely at the level where we would see anything at all," he adds.

"Even if we don't find something in 2015, it most likely just means that either we were unlucky or else our understanding of how frequently these events should happen in nature is off," Hanna says. "The question is whether there will be sources in our nearby universe that will produce them with enough strength."

There already is indirect evidence of gravitational waves. But measuring them directly would tell physicists whether general relativity, Albert Einstein's theory for how gravity works, holds up.

That is important to understanding how the universe works, Hanna says. "There are a lot of interesting things this would answer."

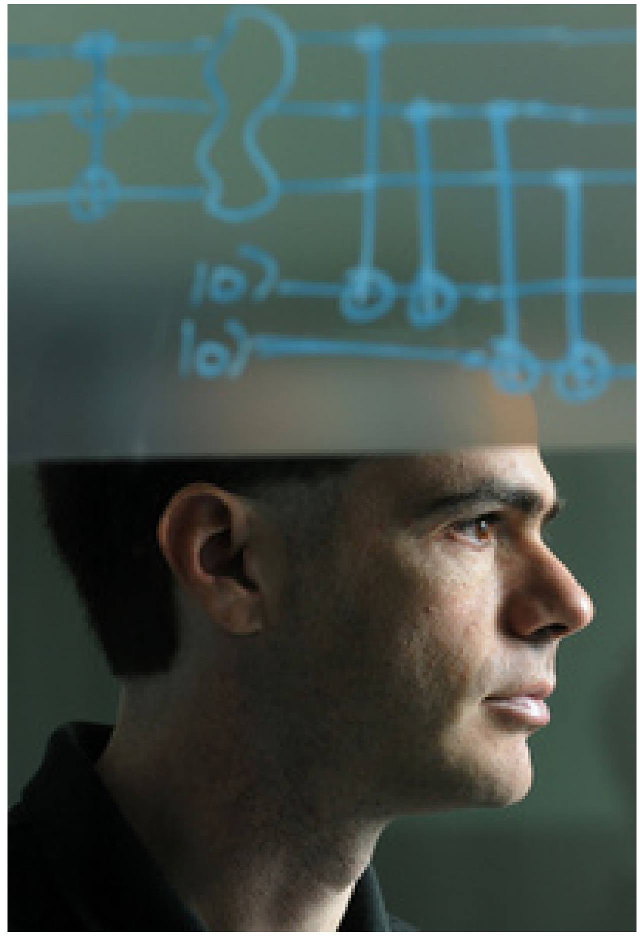
http://www.therecord.com/news/business/article/596002--seeking-ripples-in-space-time

WATERLOO REGION
RECORD

The next computer revolution

Written by: Rose Simone

Date: September 17, 2011



Daniel Gottesman Researcher Daniel Gottesman with a drawing of an error correction circuit at the Stephen Hawking Centre of the Perimeter Institute, where he is exploring the possibilities of quantum computing.

WATERLOO — Thirty years ago, when desktop computers started showing up, they were clunky, slow, cranky and prone to breakdowns.

But they were also revolutionary. They changed the world.

Today, people carry computers in the palms of their hands. Today's BlackBerrys, iPhones and other smart phones have computing power undreamed of 30 years ago, which leads to the question, what will computers be able to do 30 years from now?

That's a question that Daniel Gottesman, a researcher at the Perimeter Institute for Theoretical Physics, thinks about. He works on the theoretical limits and possibilities of something even more fantastic than any technology we have now: the quantum computer.

"Small quantum computers have been built. They are already here," he says. "But for the bigger ones that can do more complicated things, I would say that could happen in 20 or 30 years."

Quantum computers work on fundamentally different principles than today's computers. Instead of using electrical signals to generate information in "bits" of zeros or ones, quantum computers would process information in "qubits" using atomic particles in a strange "superposition" of zero and one at the same time.

The quest now is about how to maintain control of a larger number of qubits, to make these quantum computers do things that are our regular computers cannot do. They might, for example, help experts in condensed matter physics develop fantastic new materials with strange and unique properties.

Gottesman is one of the physicists laying the ground work for this revolution.

Part of his job is to work on quantum computer error correcting codes that fix the errors that are bound to happen because the qubits are in a delicate state that can easily break down.

He also works on figuring out what types of problems quantum computers should be good at, and more importantly, what their limits are. "That helps to inform us about the properties of quantum information," Gottesman says, adding that it also has applications in quantum cryptography, the business of keeping information secure.

Gottesman has been at the Perimeter Institute for more than eight years, making him one of the long-standing physicists there.

"When I first got here, nobody (in the global physics community) knew what the Perimeter was. Now, certainly in the areas that we do research, I think everybody knows us," he says.

"It is a good environment to do work at the highest level."

http://www.therecord.com/news/business/article/595914--the-next-computer-revolution

WATERLOO REGION
RECORD

On the dark side of the universe

Written by: Rose Simone

Date: September 17, 2011

Dark matter Philip Schuster, left, and Natalia Toro are researchers involved in the search for Dark Matter and the possibility of a fifth force, a dark force, in the universe.

WATERLOO — There is something strange at work in the universe.

Physicists don't know what it is. They don't know what it is made of. They can't see it, not directly at least. They just know it is something mysterious, something dark that is holding galaxies together.

They have even given it a suitably mysterious name – "dark matter."

Natalia Toro and Philip Schuster are among the new young physicists at the Perimeter Institute for Theoretical Physics who are doing the theoretical work for experiments that might help to figure out what dark matter is.

"Not only is it not producing light, but light doesn't even know that it is there," Toro says. "It doesn't interact like ordinary matter. It doesn't produce light or interact with light. So what is it?"

Physicists want an answer to this question. "Without this stuff, our galaxies would not bind together in the way that they do," says Schuster. "This accounts for the bulk of the binding energy. So it is important to our existence."

One possibility is that our understanding of gravity is too shortsighted. The theories we have work well in our local pocket of the universe, but it is possible that gravity behaves differently on a galactic scale in the far reaches of cosmos.

There are physicists working on such modified theories of gravity, although none of those theories has been widely accepted as the explanation.

Another possibility is that dark matter is made up of particles of some sort, but not like the particles we know of now. They would be more like ghostly particles that pass through the matter we know of, so we can't detect them easily.

"This idea has been around for a long time — that you could have matter in the universe that is just like the stuff we are built out of, but it doesn't interact with us," Schuster says. Because of certain anomalies that have popped up in some satellite experiments, there is a resurgence of interest in this idea, he says.

One of the experiments that Toro and Schuster are doing theoretical work for is taking place at the Thomas Jefferson National Accelerator Facility in Virginia.

One exciting possibility is that if dark matter is made of particles, those particles might be mediated a new type of new force – a dark force. If that is true, it would revolutionize physics.

Right now, in the standard model of physics, there are four forces of nature, including gravity and electromagnetism, as well strong and weak forces that govern how the nucleus of atoms stick together and how things decay.

But this dark force would be another force, "a fifth force," Toro says.

Not only would that revolutionize our understanding of the universe, "it is something that could be useful in the future," adds Schuster. "We have made pretty good use of the forces we know of so far."

Toro and Schuster are also involved in trying to understand the data coming from the experiments taking place at the Large Hadron Collider deep underneath the ground near Geneva, Switzerland. Those experiments are part of a quest to understand what the universe is made of, at the most fundamental level.

That, in and of itself, is an exciting goal. “Over the past couple hundred years, we have made a lot of progress in figuring out how things work and the impact that has had on our world is hard to overstate,” Schuster says. “But also, who doesn’t want to know things work?”

http://www.therecord.com/news/business/article/595912--on-the-dark-side-of-the-universe

Ontario physics institute grabbing top scientists

Written by: Peter McMahon

Date: September 25, 2011

WATERLOO, Ont. — Star power was out in full force last weekend, and not just for the Toronto film festival wrap-up.

A who's-who of Canadian celebrities -- from astronauts Julie Payette and Steve MacLean, to "man-in-motion" Rick Hansen, to songwriter David Foster, to William Shatner -- gave in-person and video tributes to the world's most famous living scientist: Stephen Hawking.

Guests tour the innovative 'Sky Room' at the newly-opened Stephen Hawking Centre at Perimeter Institute for Theoretical Physics during Doors Open Waterloo on Sept. 18. (photo gallery included online)

The occasion: the opening of the Stephen Hawking Centre at the Perimeter Institute for Theoretical Physics in Waterloo, Ontario.

"Special places like Perimeter encourage young scientists to be ambitious and bold," Hawking said in an appearance via video.

"History shows us today's theoretical physics is tomorrow's technology," he continued, thanking the unique partnership of government and industry that made the building possible.

When fully occupied, the $29-million, 55,000 square-foot Hawking wing will allow Perimeter to house the largest concentration of foundational theoretical physicists on Earth.

So how did the city of Waterloo get to be a world hotbed for unlocking the secrets of the cosmos?

"We've seen the incredible benefits that theoretical physics has played in our society," said RIM-co-CEO Mike Lazaridis at the opening.

Realizing the importance in investing in theoretical physics in the late 1990s, Lazaridis would eventually contribute a quarter-billion dollars of his own money to help found and support Perimeter and the nearby Institute for Quantum Computing.

The new wing is the first facility specifically built for theoretical physicists. A hipper, more fun version of the stylish original building, the Hawking Centre looks like a spaceship wrapped around the outside of the existing Perimeter Institute. Inside, it's a glamorous meeting of math and art -- as if the building itself is daring the most boring person on the planet to be creative.

"You have little alcoves with blackboards and a very high degree of visibility through almost the whole building so you can spot an interesting colleague to talk to from almost four stories away," said Perimeter director and Hawking collaborator Neil Turok.

Turok, Lazaridis and others hope the institute will be a haven of peace, collaboration and creativity that will bring the world's greatest minds that much closer to solving the mysteries of what we are and how we came to be.

The building

To help raise the bar on Perimeter's already world-renowned culture ("there are no ‘groups' here," says Turok, proud that the organization nurtures collaboration across disciplines and generations), Teeple Architects of Toronto have created a truly imaginative space in the Hawking Centre -- one where Hogwarts School of Witchcraft and Wizardry seems to have collided with the Starship Enterprise (ironic, since the cutting-edge research here might have been dismissed as fanciful hocus-pocus decades ago.)

On the way from their office to talk out an equation with a colleague, a researcher might navigate one of a dozen glass-bordered staircases and catwalks that weave straight through floors (there's even a three-and-a-half floor meeting space between the third and fourth floors) leading into nooks full of gutsy angled ceilings, elliptical skylights, and collaboration lounges whose glass writing walls peer down into lower floors on one angle, then become opaque on another.

In the middle of the second floor by the two-storey Black Hole Bistro is a landscaped herb garden -- one of a half-dozen green spaces within the borders of the building. The building itself is surrounded by several acres of green space and a number of wooden-bridge-crossed reflecting pools.

As with the original building, practically any wall that isn't glass is covered with blackboard space: One black wall in an outdoor fourth-storey lounge was immediately claimed as blackboard space by researchers who never realized the wall was simply metal that just happened to be black.

The people

Perimeter has already put Canada on the map by snagging some of the world's most prominent scientists, including Hawking himself, who will be making regular research visits, and – just this week – MIT superstar Xiao Gang-Wen: a "game-changer" (in the words of PI director Neil Turok) who will now call Perimeter his full-time home.

In an area of science where commercial applications are often decades or more away (in some cases, we're still just starting to reap the benefits of Einstein's theories), scientists at Perimeter have already made discoveries in the decade-or-so since the institute opened. Among some of the most recent:

- Latham Boyle -- helped develop a theory for how to detect super-massive black holes through gravity waves longer than the diameter of the entire Earth.
- Raymond Laflamme -- along with several colleagues -- confirmed a key rule of standard quantum theory (which says that every particle in the universe behaves like a particle and a wave) with more accuracy than any other group has so far.
- Luis Lehner developed an "early-warning system" for merging black holes, so scientists can locate and study pairs of these cosmic demons that are in the early stages of merging into one.
- Zhengfeng Ji gained new insights into when quantum computers are the right tool for the job, and -- perhaps more importantly -- when they're not.
- Jaume Gomis and Takuya Okuda created new tools to study the strong nuclear force (one of the four basic forces of nature – another one being gravity), while Freddy Cachazo has found new theories to use particle accelerators like the Large Hadron Collider to help study such forces.

"It's a huge opportunity to work in such an inspiring place," said Turok, as two espresso-toting colleagues leaned toward each other across matching comfy couches to riff on another idea. "Now, we have to live up to it by advancing the science as soon as possible."

http://www.ctv.ca/CTVNews/SciTech/20110922/waterloo-physics-institute-grabbing-top-scientists-110924/

The Economist

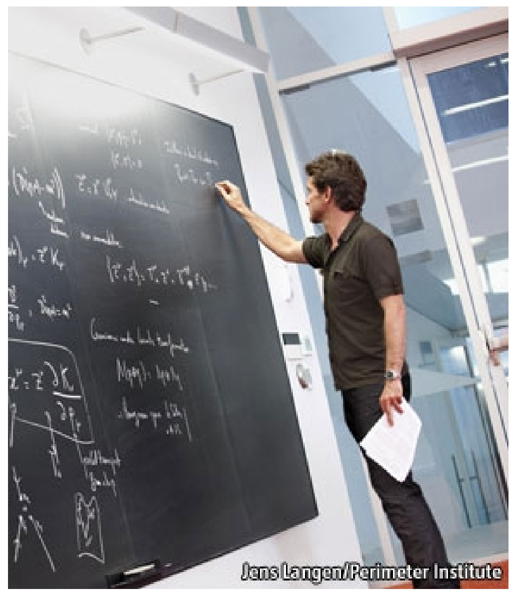
Stretching the perimeter

Written by: Jan Piotrowski

Date: September 29, 2011

Physics cannot subsist on experiments alone

UNLIKE experimental physicists, with their big, expensive toys (see article), theorists content themselves with blackboards, coffee and—crucially—a free rein. Perimeter Institute for Theoretical Physics (PI), in Waterloo, Ontario, which has just opened a snazzy, new wing named after Stephen Hawking, the world's most famous living physicist, offers all three.



And this term proves my salary is too small

PI was set up in 1999 by Mike Lazaridis, founder and co-CEO of Research in Motion, the maker of the BlackBerry range of personal digital assistants. Mr Lazaridis, a physics buff and fan of Dr Hawking since his days as an engineering student at the University of Waterloo, in the early 1980s, has stumped up C$170m ($165m)—a quarter of his personal wealth—to help endow his brainchild.

The new wing, which has absorbed C$29m, doubles PI's capacity, to over 200 researchers, making it the world's biggest institute for the study of theoretical physics. The humming brains it accommodates are working on a range of problems at the cutting edge of the subject: superstring theory, quantum-loop gravity, condensed-matter physics, complex systems and quantum information—the last of which involves PI's single concession to experimental science, the sending of quantum-encrypted messages between it and the nearby Institute for Quantum Computing.

A breakthrough in any of these areas would be the stuff of Nobel prizes. In time, it might also be the stuff of new technology. Even the most abstruse fields, Mr Lazaridis observes, yield practical benefits in the long run. He calls fundamental theorising "the most high-impact, low-cost pursuit in science". He should know. The BlackBerry itself would be impossible without theoretical insights developed 100 years ago by the first quantum physicists. Come back, then, in another century to find out if the whole exercise has been worthwhile.

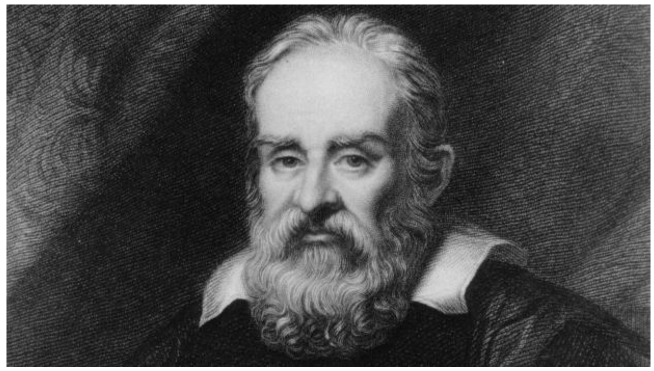
http://www.economist.com/node/21530943

THE GLOBE AND MAIL

Great science opens doors to the future

Happy 448th birthday, Galileo: The brilliant astronomer's birthday provides a timely occasion to reflect on how science has transformed our world and how it will govern our future.

Written by: Neil Turok
Date: February 15, 2012



The approaching birthdays of two renaissance polymaths, Nicolaus Copernicus (Feb. 19, 1473) and Galileo Galilei (Feb. 15, 1564), provide a timely occasion to reflect on how science has transformed our world and how it will govern our future.

Copernicus and Galileo discovered nature's underlying, mathematical simplicity by looking far beyond our everyday experience, using a combination of reason, careful observations and experiment. It took a leap of imagination to realize that, despite appearances, the Earth we stand on is flying around the sun, like a great spaceship, at 30 kilometres a second. The implications were profound: Copernicus liberated the Earth (and us) from the centre of the universe, revealing a world of limitless possibility, and Galileo discovered the basic principles of motion, laying the ground for all of modern engineering.

Great science opens doors to the future. Copernicus and Galileo – and Newton, Maxwell and Einstein, who came after them – set the stage for an age of enlightenment and progress. By seeing through the flaws in current thinking, and looking boldly beyond, they discovered laws of almost magical power that, in time, formed the basis for every modern technology, from computers to space rockets, from cellphones to NMR scanners.

Whether or not their names appear in newspapers, similar forward thinkers exist today. The past two decades have witnessed a revolution in our understanding of the universe – what it's made of and what forces govern it. I am fortunate, in my position, to interact with some of today's most brilliant minds – particularly young, rising talent – whose work is seeding new theories and new understanding that will lead to new technologies likely to be equally vital to our future.

In 2012, humanity is faced with challenges that feel overwhelming and insoluble – such as climate change, food, water and energy shortages, ecosystem damage and a population explosion. But if we can learn anything from our past, it's that we've only scratched the surface of our capacity to discover, improve and achieve great things through science. We now know how to eradicate deadly diseases, how to share information around the globe in a flash, and how to map the entire visible universe – achievements Copernicus would have found mind-boggling. And we have seen how countries such as Brazil, China and India have, by unleashing their people's productivity, transformed themselves from underdeveloped nations into economic superpowers.

Science and the education that unlocks new talent are the tools that will allow us to face the future. Instead of becoming paralyzed with anxiety over the problems that confront us, we should embrace education and science as sources of optimism. Working as a global civilization to make the most of our assets – especially the minds of our young people – through strategic, long-term planning and investments, we must seek the breakthrough advances we need before the breaking points come.

This week, as Canada welcomes the world's scientific community to meet, share discoveries and contemplate the future, let us commit to working together to make education more effective and empowering, and to globally accelerate the pace of discovery and innovation. For only then will we be able to solve the problems of today and navigate a path to a bright future.

Neil Turok is director of the Perimeter Institute for Theoretical Physics in Waterloo, Ont. He is also co-chair of the annual meeting of the American Association for the Advancement of Science that opens in Vancouver on Feb. 16.

http://www.theglobeandmail.com/news/opinions/opinion/great-science-opens-doors-to-the-future/article2338555/

THE WALRUS

The Invention of Waterloo

Canada's Technology Triangle has spawned more than 450 high-tech companies, including BlackBerry pioneer Research in Motion. But it didn't just happen: an upstart university had the brains to embrace mathematics.

Written by: Don Gillmor
Date: January/ February 2012 Issue

ON THE SURFACE, Canada's Technology Triangle — comprising the twin cities of Waterloo and Kitchener, Ontario, and Cambridge to the immediate south — reflects the development Richard Florida described in his 2002 bestseller, The Rise of the Creative Class. In 2007, Waterloo, with a population of roughly 120,000, was named Intelligent Community of the Year by the Intelligent Community Forum, which cited the region's 334 technology companies (now listed as more than 450), its post-secondary institutions (the University of Waterloo, Wilfrid Laurier University, and Conestoga College), the co-operation between business and academia, and the high levels of philanthropy and local reinvestment.

The Waterloo region's evolution followed a familiar North American pattern. It started as an agricultural community, grew into an industrial base and urban hub, achieved rapid expansion (in 1965, Kitchener was the fastest-growing city in Canada), then watched as its industries died and the downtowns hollowed out. The area started with gristmills, and proceeded through tanneries, breweries, television plants, and shoe factories, most of them gone now. Waterloo has been named both the Button Capital and the Rubber Capital. But the city lost manufacturing jobs to offshore concerns, to economic and cultural shifts, and to the rise of the Canadian dollar. Unlike hundreds of similar cities that dot America's Rust Belt, though, Waterloo went on to flourish.

Part of this has to do with the region's curious historical combination of conservatism and entrepreneurial spirit, its ability to adapt to new industries as old ones die. Manufacturing remains the largest employer, but it also registered the largest sector decline between 2001 and 2006. The technology sector, while smaller, is the fastest growing.

Technology is viewed as the holy grail of modern economies. It brings in jobs and money; it brings the future. A lot of energy is spent attracting it, growing it, and nurturing it, with varying degrees of success. Waterloo's tech sector is often equated with BlackBerry pioneer Research in Motion, which has its headquarters there. The two are viewed in lockstep, the way General Motors was linked to Flint, Michigan. But, in fact, Waterloo's technology boom began more than fifty years ago, and at the centre of it stood the University of Waterloo.

THE UNIVERSITY was established in 1957 by two local businessmen. One of them was Gerry Hagey, a public relations man for the B. F. Goodrich tire company who became the university's first president. UW's initial focus was on producing actuaries for the local insurance companies, and engineers to accommodate the postwar industrial boom. Hagey implemented a co-op program that had engineering students enter the workforce for four months of the year while they earned their degrees, a course of study that began in the early '60s and eventually expanded to other disciplines at UW. He had seen versions of the program in the US and thought it would work at UW. But the university was just getting started, and the curriculum was greeted with disdain by established institutions. At the time, a deep sense of distrust existed between industry and academia: universities considered industry a crude, bottom line culture, while industry found academics irrelevant and out of touch. Both groups had a case, and Hagey thought each would benefit from exposure to the other.

Most Canadian universities began with either a religious affiliation or an emphasis on the humanities. The University of Waterloo began with engineering, mathematics, and science, at a time when these weren't especially prized. In the early '60s, math (like philosophy and English literature) was studied by people who loved the discipline; it had little practical application other than teaching like-minded thinkers who came afterward. But the head of the math department, Ralph Stanton, had the vision to see that his field would become increasingly integral to modern life. He had written a textbook on numerical analysis, a branch of mathematics that is closely aligned to computing. In 1960, the university established its Computing Centre, and suddenly math had a practical application. The department grew so quickly it was expanded in 1967 into a separate faculty, the first in North America.

At this point, computers were still mostly bungalow-sized machines that sat in large, locked, heavily cooled rooms. The centre was run by Wes Graham, who was innovative in letting undergraduates use the equipment. IBM credited him with democratizing what was still an esoteric and largely elitist world, and he eventually received the Order of Canada for his contribution to computer science. Given access to the machines, students responded by designing early computer languages (WATFOR and WATFIV) that were later adopted by universities around the world, including the Massachusetts Institute of Technology. He also formed a campus group to distribute the software, and that evolved into a computing company, Watcom, the first of many to be spun out of the university.

By 1984, UW claimed one of the world's largest computer science programs. At the time, universities were among the biggest markets for computers, and manufacturers courted them heavily, assuming students would end up buying whatever they had used at school. IBM was the giant then, and it offered computers to universities at 80 percent discounts. Digital Electronic Corporation, an IBM competitor, upped the ante in 1984 by giving UW $25 million worth of equipment, further expanding students' access.

The school continued to develop its science and technology base through several proactive presidents, including Doug Wright, who served from 1981 to 1993 and had been with the engineering department since the beginning. He and another engineering professor initiated a policy whereby students and staff retained the intellectual rights to whatever they developed. This turned out to be a critical decision. Some universities (Stanford, the midwife to Silicon Valley, being the notable example) follow the same policy, but others (like the University of Toronto and Harvard) retain some intellectual rights. However, Wright says, schools that give up patent rights tend to gain more net benefit than those that don't. The practice creates incentive, and there's little downside, as a single patent isn't much use. "You need an armload to open a business," he says. The arrangement also helps foster a symbiotic relationship between the outside world and the school; UW has spawned more than 250 science and tech companies.

OpenText turned out to be one of the most important. In 1984, UW secured a contract from Oxford University Press to computerize the Oxford English Dictionary. Wright received a letter from a British friend who had noted the approaching end of the OED's copyright and was looking into digitizing the twenty volumes. "The publisher realized that the technology was very important," Wright told me, "and that English was becoming the international language for business and technology." He went to England and met with IT personnel at Oxford University Press, and said UW had the expertise to take the OED into the digital age. No one had heard of Waterloo, and there wasn't much enthusiasm for using a Canadian university. Back home, the tech people at UW were equally unenthusiastic. They had no interest in the seminal dictionary, and were unconvinced the project would be a worthwhile exploration of computer science.

The University of Waterloo's Institute for Quantum Computing; and one of its mobile units

It turned out otherwise. Through Wright's efforts, the university won the contract (beating out IBM and Lockheed, among others), though it took months of convincing on both sides. But the search technologies UW developed led to the founding of OpenText, which went on to become Canada's largest software company, with 4,400 employees. Those search technologies were later adapted by Yahoo!, giving it the ability to search every word on every Web page.

That same year, Mike Lazaridis, a UW engineering student who had grown up in Waterloo, asked Wright if he could leave the program to pursue his business interests; he felt he could always return and finish his degree. As president, Wright officially counselled him to finish but privately offered encouragement for his business plan. In March 1984, Lazaridis, along with a childhood friend, Douglas Fregin, incorporated Research in Motion.

RIM grew into a multibillion-dollar tech powerhouse, bringing highly paid employees (estimated at between 7,000 and 8,000) to the area, and fostering a strong relationship with UW, where it has found many recruits. Equally important was how the executives chose to spend their new wealth. Lazaridis has given $170 million of his own money to establish the Perimeter Institute for Theoretical Physics. The idea behind Perimeter was to create an environment for the world's leading physicists to pursue super string theory or inflation theory, or to figure out what exactly banged during the big bang, with no commercial pressures — though, as Lazaridis pointed out to the institute's first director, Howard Burton, the BlackBerry was essentially based on nineteenth-century physics. "Imagine," Lazaridis said, "what we could do with twentieth-century physics or twenty-first-century physics."

While Lazaridis was trying to reconcile the fundamental laws of nature, his co-CEO, Jim Balsillie, decided to address world politics and government. In 2001, he donated $20 million to establish the Centre for International Governance Innovation in Waterloo. In 2009, he gave $50 million to UW, nearby Wilfrid Laurier University, and CIGI, as part of an initiative to found the Balsillie School of International Affairs.

CIGI is housed in what was once Seagram's barrel warehouse for aging whisky. The building was erected in 1857, and in 1928 Joseph Seagram sold it to Sam Bronfman. When Prohibition was repealed in the US in 1933, profits soared and Seagram's became the world's largest distiller, with Waterloo a prominent centre of its operations. In its heyday, Seagram's employed 250 people. But Sam's sons watched the distillery business fade in the '70s, as people turned away from whisky and vodka in favour of wine. By the '80s, the industry was in decline. Edgar Bronfman Jr. decided to get out of the business, and Seagram's closed its doors in 1992. Edgar went on to embrace the creative class, buying into media and entertainment, and lost much of the family fortune in his bet on Vivendi Universal. Not all creative classes are created equal.

Now the site has been effectively repurposed, the new economy replacing the old. Two of the beautiful old stone Seagram's buildings were converted into condos, CIGI occupies the barrel house, and the ambitious Balsillie campus is slated to be built adjacent to it. When finished, the complex will cover the entire block.

In 2002, Lazaridis followed the Perimeter Institute with the Institute for Quantum Computing, to which he contributed $100 million. It will be housed in the newly built Mike and Ophelia Lazaridis Quantum-Nano Centre on the UW campus, to facilitate interaction with the mathematics and engineering faculties. The centre is an extension of Lazaridis' interest in physics and is devoted to pure science, but it, too, holds out the possibility of commercial revolution. Classical computers, as they are called by quantum physicists, use silicon chips to facilitate calculations. These chips have grown smaller and faster, but even the fastest classical computer only performs one calculation at a time. Rather than silicon chips, quantum computers use quantum particles, such as atoms, and the advantage is that they can make many calculations simultaneously. For simple problems, the difference is minor, but for certain complex ones the gains will be extraordinary. It will cause a revolution in security, for one thing. "Quantum computing," the institute's website reads, "has the potential to revitalize a host of existing technologies and generate new ones, to open new windows on the nature and origin of the universe, and to change the way we think about information and reality itself." This, the site states, is the beginning of an Alice in Wonderland parallel universe era, where cats can be both dead and alive at the same time. And where Scotty could, perhaps, beam you up.

Ray Laflamme, executive director of the Institute for Quantum Computing, is a lithe, athletic man originally from Quebec, and a former protege of Stephen Hawking. He convinced Hawking that in a contracting universe, time wouldn't run in reverse, and he has been a world pioneer in quantum information. Waterloo has a twelve-qubit (an amalgam of "quantum" and "bit") quantum computer, the world's largest, and Laflamme showed it to me.

The future is housed in what looks like a RadioShack storeroom, with steel shelves holding generic-looking electronics. The computer — a large canister with wires coming out of the top, surrounded by a knotty pine fence — resembles a moonshine still. Extremely sensitive to noise, light, and vibration, quantum computers are cumbersome and touchy. Using atoms to perform calculations is like asking a large class of extremely gifted kids who all suffer from separate conditions (peanut allergies, paranoia, passive-aggressive tendencies) to tackle a problem collectively. A fifty-qubit computer would be as powerful as the largest existing supercomputer. A 1,000-qubit quantum computer could solve in a few days complex problems that all the world's supercomputers combined could not. "With quantum mechanics," Laflamme says, "we are learning how to speak the language of atoms and molecules. Before, we could look at the effects, but we could hardly control them. Now we have the right language, the right tools, the right methods of controlling them."

A commercial quantum computer isn't imminent, but when it does arrive, in ten or twenty (or fifty) years, Silicon Valley will be eclipsed by Quantum Valley, and Waterloo will be poised to capitalize on the moment. In part through Lazaridis and Balsillie, Waterloo has a focus that is both global and universal, and that looks to the future. But the local and the present are still where everyone lives, where Balsillie and Lazaridis live. What kind of city does the creative class create?

Waterloo's Centre for International Governance Innovation, housed in a nineteenth-century Seagram's building; and its new, contemporary entrance

WATERLOO, LIKE HUNDREDS of other small North American cities, experienced a golden moment when its main street bustled, when its architecture was comforting brick, and its people were employed and churchgoing and filled with optimism. But this proved transitory; the city grew on the fringes, and the schools moved to the edges, followed by residential and commercial development. Big boxes stores sprouted on farmland, and the main street crumbled. Industry withered, jobs disappeared, and young people fled to the big city.

Walking down King Street, the historical artery that snakes southward through Waterloo and Kitchener, you see the usual signs of urban decay: tattoo parlours, second-hand stores, dollar stores, and that harbinger of poverty, the cheque-cashing outlet. These are leavened by hopeful restaurants, by ambitious architecture, such as Kitchener City Hall and UW's School of Pharmacy building, and by the successful repurposing of older industrial structures into other uses — shoe factories and distillery buildings converted into lofts, tanneries into retail and commercial space. At the corner of Erb and Caroline Streets stand three complexes that have won the Governor General's Medal in Architecture: the Perimeter Institute, the Canadian Clay and Glass Gallery, and CIGI. The city is recovering from the blight familiar to every urbanite.

"Fifteen years ago, the cores were in disrepair," says Rick Haldenby, director of UW's School of Architecture, as well as of the Centre for Core Area Research and Design, which looks at the particular challenges facing mid-size cities. "Kitchener was a basket case," he says. "When we started the mid-size centre, we focused completely on core area redevelopment and revitalization. In Kitchener, they tried to fix the problem by building two malls downtown. Both of them were disastrous. Waterloo built a suburban mall downtown, with parking around it." It looks pristine and bereft. The mall solution didn't work. Nineteen were built in small Ontario cities in the past two decades, and all of them failed. The faux suburban lost out to the true suburban.

“We need a far more integrated view of urban planning, a greater quantum approach,” Haldenby says. Cities are essentially binary; they are arguments with themselves (rich versus poor, core versus suburbs, cars versus public transit). Caleb Rosado, a professor of urban studies at Eastern University in St. Davids, Pennsylvania, argues that quantum physics, with its holistic qualities, is the way to approach urban planning. “The erroneous prevailing world view limiting urban studies and urban transformation,” he writes, “emerges from classical physics… Quantum physics with its non-dualistic approach to life provides an approach that will enable urban workers to literally think outside their prevailing paradigms… one that shifts thinking from fragmentation to wholeness.”

Cities are already quantum, in the sense that everything happens at once: death, sex, final sales, zoning infractions, Starbucks, soul-destroying commutes. But they tend not to be holistic. The suburbs were created as a means of separation, to provide an oasis for the middle class away from the ills of the city. But now the world is about integration; from university disciplines to urban planning, the move is to link everything, to cross-pollinate.

Malls, which are hermetic and predatory, didn’t work in the Technology Triangle. What did was introducing post-secondary schools into the core. The architecture school itself was a cure, or at least the beginning of one. Cambridge lured it away from the UW campus with the promise of money and a great building, a converted early twentieth-century former silk mill on the Grand River. A key donation came from the Musagetes Foundation, started by Michael Barnstijn and his wife, Louise MacCallum, both former RIM employees. A gifted software engineer, Barnstijn joined the company in 1985 and was rewarded with a 20 percent stake. He left in 1998, and his contribution to local culture forms another philanthropic ripple that extends outward from the RIM centre. Four hundred and fifty students attend the architecture school, and most live within walking distance. The number of residential units in downtown Cambridge has more than doubled since the school opened in 2004, and amenities have sprung up to service them, bringing life to the picturesque core.

Kitchener used the same approach as Cambridge to restore its downtown core, luring UW’s pharmacy school to a prominent intersection. The building, a festive modernist box with images of leaves and flowers and medicinal herbs on the exterior, was designed by Hariri Pontarini Architects. In 2006, Wilfrid Laurier University located its Faculty of Social Work in downtown Kitchener.

In Waterloo, where civic life congregates mainly around the campuses, some research centres (Perimeter and CIGI) have moved off site. The point isn’t just the effect of bringing students to the core, but the impact of the buildings themselves. Using architecture as a force for urban renewal isn’t new, but it has been bowdlerized by a wave of trophy projects that attract attention while neglecting the urban fabric. They provide fleeting interest but do little for city building, and in the worst cases look stranded, conveying the sense that the circus has left town.

One of the principal firms involved in Waterloo’s physical renaissance is Toronto’s Kuwabara Payne

McKenna Blumberg Architects. Its relationship with the region began in 1989 when Bruce Kuwabara designed Kitchener City Hall, with a welcoming public square and a skating rink to provide an anchor on a street that was losing ground. The firm also did the Grand Valley women's prison outside Kitchener, an innovative and controversial experiment in changing behaviour through environment. The massive, 26,000-square-metre Quantum-Nano Centre, which will house the Institute for Quantum Computing, was designed by Marianne McKenna and Mitchell Hall of KPMB and is set to open in 2012.

Kuwabara and his partner Shirley Blumberg are now doing the Balsillie Campus, which is clustered around the old Seagram's building downtown. "Every building implies a city," Kuwabara says from the open boardroom of his Toronto offices. "If you put in big boxes, you imply suburban. But now the urban is being restored."

Today the world is about connectivity and sustainability, and KPMB designed the buildings to promote those qualities, connecting among different disciplines as well as between school and city.

One key to Waterloo's success has been the integration — economic, geographic, and cultural — between the universities and the city. Like the engineering and computer faculties, the architecture school is integrated into the community. "We are involved in almost everything," Rick Haldenby says, "every major committee in Cambridge, Kitchener, and Waterloo. We've advised on virtually every major development in the region." Kuwabara suggests that the UW architecture school is the best in the country.

It is the only non-metropolitan one in Canada. "It's a question of scale," Haldenby says. "It wouldn't make a difference in Toronto, but it does here. Here you can change the course of history, and we have." Like the area itself, the school is pragmatic.

A light rail transit system is being built to link the three cities, and, perhaps more critical, distribute students around the region; many now congregate near the UW and Wilfrid Laurier campuses. "There are 50,000 students in the area," says John Jung, CEO of the regional development entity Canada's Technology Triangle Inc. "We'd like to spread them around. Transit is key."

WATERLOO'S SUCCESS is anomalous: the modern era hasn't been kind to small cities, and it is increasingly a case of go big or go home. The megalopolis constitutes the twenty-first century's most potent urban form. The Greater Toronto Area, an hour away, has roughly five and a half million people. The world now has fourteen cities with populations of 11 million or more, and that figure is climbing quickly. At the other end lie cities that are losing population, that are becoming small, but not by choice. Buffalo has 270,000 people, fewer than in 1900; Cleveland is half the size it was in 1950. Detroit is less than half its former size and may never recover; one proposal suggests returning parts of the city to farmland. But the people leaving these cities aren't going to smaller centres; they're going to the big city. The US is littered with Rust Belt casualties.

It wasn't supposed to happen this way. A few decades ago, small cities were touted as the future. As big cities became uninhabitable, plagued by crime, congestion, pollution, and sagging infrastructure; as the Internet made it possible to work from anywhere; as Wall Street and Bay Street were decentralized into the ether, we would choose to live in small, livable cities because we could. But we didn't. We huddled in large centres.

Especially in Canada, where cities have the ineffectual political sway of a municipal utility, some of them are hampered by overlapping jurisdictions, by competing interests (suburban versus urban), by short-sighted decisions, and, most potently, by indecision. Greatness has eluded all of us. The case for smaller centres has once again become compelling, though we need imagination, political will, and the resources to pull it off.

The resources in Waterloo have come partly in the form of philanthropy: the hundreds of millions the RIM executives have contributed, which has prompted others to donate. It helps, too, that they have chosen specific targets involving not just meaningful architecture, but institutions that could have a significant impact on both science and the local economy.

Of course, the quantum revolution may fizzle; Laflamme admits it may not be the key to understanding nature. RIM, like Nortel, may crumble, its new technology unloved, its management hounded out of office (shares have plummeted by more than two-thirds in less than a year). But whatever its fate — bought and dismantled by foreign vultures, protected as a national resource (the IT version of potash), succumbing to quiet decline, or undergoing an unexpected renaissance — the lessons for city building remain. The management of resources (youth, technology); the tangible benefits of architecture; and the integration of academia, government, and the private sector serves as a valuable model, one that big cities should emulate.

http://walrusmagazine.com/article.php?ref=2012.01-cities-the-invention-of-waterloo&page=

nature

Physicists hunt for dark forces

Written by: Eric Hand
Date: April 3, 2012

The Jefferson Lab's Free-Electron Laser is a low-cost option in the bid to discover dark-sector forces.

In tunnels beneath the Thomas Jefferson National Accelerator Facility in Newport News, Virginia, an accelerator whips a beam of electrons around a racetrack. Their energies are modest, but the beam is tightly packed with them — for it takes a very bright beam to detect a photon that doesn't shine.

In a three-week experiment due to start on 24 April, the electrons will crash into a thin tungsten target at 500 million times a second, creating a cascade of short-lived particles. Amid the debris, physicists with the Heavy Photon Search (HPS) are hoping that they will find signs of something exceedingly rare: a 'heavy' or 'dark' photon. The discovery would open the door to an unseen world of dark forces and dark atoms that theorists have long speculated about — and could help to pin down the dark matter that is thought to comprise 85% of the matter in the Universe.

The HPS researchers at the Jefferson Lab are quick to concede that the experiment, like two others at the lab probing this dark sector, is a long shot that is likely to achieve little more than null results. But the reasonable price tags for such projects — about US$3 million to build and run the HPS detector — have prompted more physicists to try. "It's always a great question in physics to go around wondering if there are more fundamental forces," says physicist John Jaros, co-spokesman for the HPS experiment.

The dark photon, unlike conventional photons, would have mass and would be detectable only indirectly — after the dark photons have decayed into electrons and positrons (the antimatter counterparts of electrons). Yet, like the familiar photon, which carries the electromagnetic force, the dark photon would carry a force — a new fundamental force in addition to the four that we already know about. It would be the first sign of a hidden sector, which could include entire zoos of new particles, including dark matter. "It would be like when Galileo saw moons orbiting Jupiter," says Nima Arkani-Hamed, a theorist at the Institute for Advanced Study in Princeton, New Jersey.

Theorists had hoped that the Large Hadron Collider — the world's highest-energy (and most expensive) particle accelerator at CERN, Europe's high-energy physics lab near Geneva, Switzerland — would open the door to new concepts such as supersymmetry, a set of theories that would resolve some of the problems in the standard model of particle physics. But, so far, it has yielded no clues, such as the dark-matter particles predicted by some supersymmetry models. “The null results are not making people happy,” says Philip Schuster, a theorist at Canada’s Perimeter Institute for Theoretical Physics in Waterloo, Ontario. “People are wondering what other possibilities are out there.”

Instead, some physicists are turning to the ‘intensity frontier’ — creating many collisions and teasing rare events from the wreckage. The electron beams at the Jefferson Lab are not the most powerful, but they are extremely intense.

The idea for a dark sector was first proposed in 1986 (B. Holdom *Phys. Lett. B* 166,196–198; 1986), but remained largely unexplored until a group of theorists, including Arkani-Hamed, resurrected the theory a few years ago (N. Arkani-Hamed *et al. Phys. Rev. D* 79, 015014; 2009). The group embellished the idea in light of results from a 2006 satellite mission called PAMELA (Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics), which had observed a puzzling excess of positrons in space. Theorists suggested that they might be spawned by dark-matter particles annihilating each other. But the heavy particles most often suggested (WIMPs, weakly interacting massive particles) would have also decayed into protons and antiprotons, which weren’t seen by PAMELA. A dark-matter particle from the dark sector — “even darker matter”, quips Arkani-Hamed — would be seen only through a decay involving the force-carrying dark photon, which would make positrons but not antiprotons.

Another motivation came from an intriguing result reported in 2004 by physicists at Brookhaven National Laboratory in Upton, New York. They found that the magnetic moment created by the spin and charge of the muon, a short-lived particle similar to an electron, did not match the predictions of the standard model. This anomaly, called the muon g-2, could also be rectified by a dark-sector force, says Arkani-Hamed. He adds that the idea is not as crazy as it sounds. “The whole set-up is totally vanilla and conservative from a theorist’s point of view,” he says.

The predictions can be tested cheaply and relatively quickly. The main 6-gigaelectronvolt electron beam at Jefferson Lab has the right energy to probe the most likely mass range for a heavy photon. After the HPS’s three-week test run, the beam will be shut down for an upgrade that will double its energy. This will allow the HPS and another project, the A Prime EXperiment (APEX), to explore other parts of the dark sector in 2015. A third proposal, called DarkLight, would use the beam that drives the lab’s free-electron laser to look for heavy photons at lower energies (see ‘Feeling in the dark’).

Arkani-Hamed says that he won’t be surprised if the future path of particle physics emerges from modest experiments such as those at the Jefferson Lab, rather than from work at CERN. “It could be that these much smaller, faster, cheaper, upstart, high-intensity, low-energy experiments might actually dig up evidence for new physics before the big monsters.”

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http://www.nature.com/news/physicists-hunt-for-dark-forces-1.10386

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No Evidence for 'Knots' in Space: Theories of Primordial Universe Predict Existence of Knots in Space

Date: June 13, 2012

Theories of the primordial Universe predict the existence of knots in the fabric of space -- known as cosmic textures -- which could be identified by looking at light from the cosmic microwave background (CMB), the relic radiation left over from the Big Bang.

Using data from NASA's Wilkinson Microwave Anisotropy Probe (WMAP) satellite, researchers from UCL, Imperial College London and the Perimeter Institute have performed the first search for textures on the full sky, finding no evidence for such knots in space.

As the Universe cooled it underwent a series of phase transitions, analogous to water freezing into ice. Many transitions cannot occur consistently throughout space, giving rise in some theories to imperfections in the structure of the cooling material known as cosmic textures.

If produced in the early Universe, textures would interact with light from the CMB to leave a set of characteristic hot and cold spots. If detected, such signatures would yield invaluable insight into the types of phase transitions that occurred when the Universe was a fraction of a second old, with drastic implications for particle physics.

A previous study, published in Science in 2007, provided a tantalising hint that a CMB feature known as the "Cold Spot" could be due to a cosmic texture. However, the CMB Cold Spot only comprises around 3% of the available sky area, and an analysis using the full microwave sky had not been performed.

The new study, published June 13 in *Physical Review Letters*, places the best limits available on theories that produce textures, ruling out at 95% confidence theories that produce more than six detectable textures on our sky.

Stephen Feeney, from the UCL Department of Physics and Astronomy and lead author, said: "If textures were observed, they would provide invaluable insight into the way nature works at tremendous energies, shedding light on the unification of the physical forces. The tantalizing hints found in a previous small-scale search meant it was extremely important to carry out this full-sky analysis."

Co-author Matt Johnson, from the Perimeter Institute, Canada, said: "Although there is no evidence for these objects in the WMAP data, this is not the last word: in a few months we will have access to much better data from the Planck satellite. Whether we find textures in the Planck data or further constrain the theories that produce them, only time will tell!"

http://www.sciencedaily.com/releases/2012/06/120613102249.htm

MACLEAN'S

Why the Higgs boson discovery changes everything

Written by: Kate Lunau and Katie Engelhart
Date: July 17, 2012

For the past 22 years, Pierre Savard has, off and on, been searching for the Higgs boson particle. On the morning of July 4—shortly before physicists at CERN (the European Organization for Nuclear Research) were scheduled to present their historic findings—Savard, associate professor of experimental particle physics at the University of Toronto, awoke just outside Geneva, where CERN's sprawling complex is nestled amidst lush vineyards, with the imposing peaks of Mont Blanc as backdrop. Buried 100 m underground is the Large Hadron Collider, the world's largest particle accelerator, built at a cost of $10 billion to help physicists unravel the mysteries of the universe.

By the time Savard arose (somewhat sluggishly, as he'd been working on "Higgs analysis" until 2 a.m.), the facility's main auditorium was already full. The summer students at CERN had camped out all night. Aysha Abdel-Aziz, a University of Toronto undergraduate working on Higgs search data analysis, was monitoring Facebook at 12.30 a.m., which flashed news of a swelling crowd. "At 1:30, I thought, man, I've got to get over there," she recalls. "I got there at 2 a.m., and I'm glad I did. Because by 4 it was too late." Students hunkered down outside the auditorium to wait with sleeping bags and food and cameras.

Around 4:30 a.m., says Abdel-Aziz, a cluster of grey-haired physicists showed up. Discouraged by the lineup, which by then had snaked down the stairs and wound around the hall, they left. Savard, meanwhile, made his way to the lobby of his laboratory, where the morning's events were being live streamed. The four screening rooms were full, but he managed to hustle a chair. Displaced by their youthful proteges, the world's most seasoned particle physicists were relegated to back rooms, packed like sardines into satellite auditoriums around the complex. Some grasped bottles of champagne. Soon they would, most uncharacteristically, be shouting.

Scientists at CERN will tell you that they both knew and didn't know the results of the Higgs experiment while they sat waiting for the announcement. That's accurate. The Higgs boson particle, also known as the "God particle," or the "goddamned particle," because it's been so hard to find, was dreamed up 50 years ago to explain why everything around us has mass—essentially, why we exist.

The Higgs boson has since been the focus of the biggest hunt in the history of modern science, with CERN as the epicentre. There, the Higgs-hunting venture is conducted by two separate teams, CMS and ATLAS (short for Compact Muon Solenoid and A Toroidal LHC Apparatus), each with more than 3,000 members; they're forbidden from talking shop with each other to ensure neither's results is influenced by the other. Top physicists would have known their own group's findings. But both CMS and ATLAS needed to come up with the same numbers for anything to be conclusive.

Finding the Higgs boson, scientists say, will open the door to the study of other unknowns, like dark matter. Some have even imagined that, if the Higgs could ever be manipulated, it could lead to all sorts of science fiction scenarios, like travel at the speed of light, and more.

- PODCAST: author Kate Lunau on the story behind the biggest science story of the year.

As Savard and others scrambled for a vantage point, in Vancouver—where it wasn't yet midnight—about 40 people gathered in the auditorium at TRIUMF, a Canadian physics lab on the University of British Columbia campus, which collaborated with CERN on the Higgs hunt. Armed with pillows, coffee and Rice Krispies squares, they looked up eagerly at the live feed from Geneva. "We knew what ATLAS was showing," says Rob McPherson, a University of Victoria physics professor and spokesperson for the Canadian ATLAS team. (Canadian scientists work exclusively on ATLAS, not CMS.) "We were keenly interested to see what CMS was going to show. We were on the edge of our seats."

That scene was playing out in facilities from Aspen to Chicago to New York, where bleary-eyed scientists roused themselves in the middle of the night to watch what they sensed would be historic news. Columbia University physics professor Michael Tuts, the U.S. ATLAS operations program manager, sent out a campus-wide email to see if anybody might want to watch the results delivered live—at 3 a.m., New York time, on the Fourth of July. "I anticipated the reaction of, 'Are you totally insane?' " he says, but 75 people came, from all different faculties, "not just the high-energy physicists."

Denis Balibouse/The New York Times

In Geneva, each team announced its results to an overflowing auditorium: first CMS, then ATLAS. The presentations were methodical, delivered with the stern sobriety of an academic seminar. That is, until the very end, when a PowerPoint slide announced a standard deviation of 5 sigma—proof that they are more than 99.9999 per cent sure of their results—and the crowd burst into thunderous applause. "That's highly unusual for a physics conference," Tuts says. But of course this was a highly unusual discovery—the God particle, physics' Holy Grail, had been found.

An ecstatic grin spread across the face of CERN director-general Rolf-Dieter Heuer as he turned to face the crowd. Although scientists still label these results preliminary, “as a layman, I would say I think we now have it,” he said. “Would you agree?” More cheers. In Geneva, Vancouver and around the world, scientists popped open bottles of champagne. Peter Higgs, the 83-year-old theoretical physicist who proposed the particle in 1964, was seen in the CERN auditorium wiping away a tear.

The discovery of the Higgs boson particle has been compared to the moon landing—the biggest scientific achievement of a generation. For decades, scientists have gone on faith that it exists: the Standard Model of particle physics, a beautifully simple mathematical description of everything we know about the universe’s most basic building blocks, depends upon it. Even so, many wondered if the Higgs was just a figment of the imagination, manufactured by ivory tower theoreticians in the 1960s. After decades, a team of several thousand scientists from around the world has essentially confirmed its presence. The Standard Model is complete.

The Higgs particle tells us something very basic and fundamental about why we’re here. It is evidence of the Higgs field, an invisible force field that stretches across the universe, encasing us like a Jell-O mould, and giving mass to elementary particles within it: the stuff that makes up stars, planets, trees, buildings, animals and all of us. Without mass, electrons, protons and neutrons wouldn’t stick together to make atoms; atoms wouldn’t make molecules; none of us would exist.

At the moment of the Big Bang, 13.7 billion years ago, every particle was massless and zipped around at the speed of light. The universe began to cool and expand, and the Higgs field condensed; particles started to slow down and come together, and everything as we know it began to take shape. Without the Higgs, “the particles we’re made of would not hold together,” says Neil Turok, director of the Perimeter Institute for Theoretical Physics in Waterloo, Ont. “They would all be flying around at the speed of light, and there’d be no stopping it. The world,” he says, “would go up in a puff of smoke.”

Peter Higgs, the boson’s notoriously reluctant namesake, is often compared to his famous particle: he’s hard to spot. Shortly before the big news dropped, he was flown to Geneva, along with three other influential physicists of the same era. He tried to keep a low profile, and was spotted eating alone in CERN’s colossal cafeteria. Days after the announcement, he was back there: this time, struggling to fork up his lunch amidst a flock of buzzing admirers. In the meantime, CERN summer students had combed the laboratory halls carrying printed copies of Higgs’s original 1964 paper on the missing boson, in the hopes of nabbing an autograph. “Mild-mannered and very gentle,” is how his former colleague Alan Walker describes him. Higgs is said to cringe when the term “Higgs boson” is uttered in his presence. At times he will, rather warily, refer to “the boson which bears my name.”

Higgs’s bashfulness had been on prominent display the morning of July 4, when he entered CERN’s brimming auditorium and beelined for a seat a few rows back from the front, and somewhat off to the side. Presumably, he found the standing ovation that followed to be a bit much, but modesty seems only to fuel his new-found cult status. After the seminar, he declined questions from the press—though he granted, “It’s really an incredible thing that [the discovery has] happened in my lifetime.” His distaste for celebrity will be further tested if, as now recommended by fellow theoretical physicist Stephen Hawking—who once bet $100 against the particle ever being found—Peter Higgs becomes the recipient of the Nobel Prize.

Celebrity was a long time coming. In 1964, Higgs—then a lecturer of mathematical physics at the University of Edinburgh—published two papers outlining his theory about the never-before-seen particle. “The Higgs model” dealt with a problem that physicists had been grappling with: why do some particles have mass? And where does that mass come from? Higgs posited that particles obtain mass by interacting with a mysterious force field that permeates the universe. The Higgs boson is a sign of that field.

It was a far-out idea, although five other physicists published similar theories around the same time. The story goes that Higgs’s eureka moment took place during a quiet stroll through the Cairngorms, a mountain range in the Scottish Highlands. At that time, his area of research was considered “rather unfashionable,” he later said. Science writer Ian Sample says Higgs was “called a fuddy duddy [for] working on something that was seen as uncool.” In fact, the second of Higgs’s two papers was rejected by Physics Letters, Europe’s foremost particle physics journal, which, as it happened, was edited at CERN. Editors judged it to be “of no obvious relevance to physics.” He published it elsewhere.

It took a decade for opinions to change. In the 1970s, scientists began to see Higgs’s proposed boson—soon, the “Higgs boson”—as the missing ingredient in the Standard Model, a theory developed around that time to explain how fundamental particles and forces behave. The Standard Model is made up of 17 particles: 12 are fermions (subdivided into quarks and leptons), which make up matter. Four are gauge bosons, which transmit forces so fermions can interact. And the Higgs boson was added to explain why particles have mass.

The Standard Model isn’t perfect—it accounts for just three of the four fundamental forces, for example, because it doesn’t include gravity—but it’s by far the best explanation we’ve got of how our universe is stitched together. “Why do we have life? Why do we have planets? How did the universe form? All this is explained in the Standard Model,” says physicist John F. Gunion, author of The Higgs Hunter’s Guide. “Part of that picture is the Higgs mechanism for giving particles mass. It was the final linchpin in confirming the Standard Model,” but nobody knew if it was real. Without it, they worried, the Standard Model would fall apart.

The Higgs boson was elusive prey. For one thing, the Standard Model gave no guidance about what its mass might be, so scientists had to look across a range of possibilities. Beyond that, catching one can’t be done: after a Higgs comes into existence, it decays almost immediately into other types of particles, and theorists predicted there’d be several different “decay channels” this particle might take. To find a Higgs boson, its seekers had to create one—by smashing protons together to “shake up” the Higgs field, as Tuts says. For a long time, there wasn’t a particle accelerator powerful enough to do this. Then the Large Hadron Collider (LHC) was built.

Established in 1954, CERN was primarily an attempt to kick-start a renaissance in European physics. It was also aimed at uniting scientists who had, just a few years earlier, been engaged in a race to build bombs capable of incinerating each other. CERN is now 20 members strong (18 are EU member states), with a number of “observers” (including the U.S and Russia) and “non-member states” (including Canada). At any given time, 10,000 scientists and engineers, representing over 100 nationalities, walk CERN’s halls. It was here, in 1989, that Tim Berners-Lee wrote his proposal to create the World Wide Web, as a convenient means of sharing information between scientists. (His boss dubbed the proposal “vague, but exciting.”) The first-ever web server ran on a CERN computer, and the world’s first website was *Info.cern.ch*.

Located near the Franco-Swiss border (take tram 14 from Geneva's city centre), CERN's complex of spartan, low-rise buildings appears to be at the edge of nowhere, with nothing but a couple of gas stations in sight. Inside the gates of the facility, streets are named after dead physicists: Route Albert Einstein, Square Galileo Galilei. The grounds are quiet, though there is the steady bustle of scientists, travelling in small clusters to and from the cafeteria. A few wear suits, but the standard uniform of the particle physicist appears to be some variation of short-sleeved button-down shirt and sneakers.

The buildings themselves are surprisingly decrepit. The halls of Building 40, which houses ATLAS and CMS, are like dark, concrete tunnels. The flooring is pitted and uneven. Only posters taped to the walls—advertising a yoga society, a yacht club, and the Cinéclub's upcoming screening of *High Fidelity*—add a splash of colour. There are halls where experimentalists work, and there are wings for theorists.

A few days after the discovery of the Higgs particle was announced, the physicists who "found" it could be spotted sitting in patio chairs outside their main research site, eating heaping plates of cafeteria-prepared*moules frites* under a scorching sun. Inside, twentysomething graduate students navigated between overpriced food stations. (The meal of the day cost around $15.) The cafeteria offers physicists a respite from their dark offices, and an airy place to talk.

If CERN has the look of a high school, it has the vibe of a summer camp. Many researchers live on site, in one of a few "hostels" that are visible from the patio. Nearby apartment complexes are almost entirely occupied by physicists. Claire David, a doctoral student from the University of Victoria, lives just over the French border, in a village called Saint-Genis, which she says is about half-populated by CERN scientists. David shares a house with six other physicists, five Italians and a Brit. She rarely sees them. David tends to eat dinner in her room, in front of her computer screen and joined via Skype by friends from home. Anadi Canepa, an ATLAS physicist and researcher at TRIUMF, used to live off-site too (in her case, about 50 m from CERN's gates)—but she recently moved back into CERN hostel B39 "to save time."

"This is a really special part of work," she insists of the ever-blurred, and often non-existent, lines separating work life from personal life. Many physicists at CERN say they don't feel as if they live in Geneva at all. CERN they describe as a "complex," a "city," an all-encompassing "planet." Many CERN physicists are married to other CERN physicists. This is true of Canepa, whose husband also works in the field of antimatter. "We tend to mate" with each other, she explains, "because we never leave the lab."

That's a good thing, because work days at CERN are long—and longer still when teams are working with researchers based in other time zones. CERN does not like to favour one time zone over another. "Friends ask, 'Can we visit Geneva?' " says David. "I say, 'Yes, but I will be on call. I need to be near the detector in case my phone rings.' " She has made the 15-minute trip to central Geneva only three times since February.

CERN has a way of digging its claws into people. Savard came there in 1990, while a co-op undergraduate student at Université de Sherbrooke. His plan was to be a ski instructor, but after a winter at CERN, he changed paths, captivated by the hunt for the Higgs boson at a time when scientists were designing the early detectors that would launch the decades-long quest. "It was unbelievable. I knew that's what I wanted to do."

Nicknamed the "Big Bang Machine," CERN's current particle accelerator—which became active in 2008—is the largest machine in the world. Beyond searching for the Higgs boson, which has been its most prominent mission, the LHC was conceived to answer some of the most pressing questions in particle physics. What are dark matter and dark energy? Are there hidden, alternate dimensions all around us that we just can't access or see? What sorts of matter existed right after the Big Bang, when a hot soup of "quark-gluon plasma" filled the universe? And where did all the antimatter go? At the start of the universe, scientists believe that matter and antimatter—its twin, but with an opposite electric charge—existed in equal amounts. But today, for some reason, we're surrounded by matter, and for that we should be grateful: when matter and antimatter meet, they destroy each other.

Built underground and spanning the border of France and Switzerland, the LHC is a 27-km-long tunnel around which two beams of particles fly in opposite directions, approaching the speed of light. When these particles crash together, they produce massive amounts of energy and new mass, which are recorded in detectors at ATLAS and CMS. Scientists then sift through data, looking for patterns that might indicate a Higgs boson popped into, and then out of, existence. "It's like if you break a plate, and you only see the pieces," says Manuella Vincter, an ATLAS scientist and a physics professor at Carleton University, who holds the Canada Research Chair in Experimental Particle Physics. "You can put it back together and say, 'That's what the plate looked like.' " (According to Vincter, both CMS and ATLAS mainly observed the Higgs-like particle decaying into two photons.)

The sheer scale of the LHC is remarkable. Physicist Victor Weisskopf, a former CERN director-general, famously saw the massive particle accelerators that were built in the 1950s and '60s as "the gothic cathedrals of the 20th century," says theoretical physicist Lawrence M. Krauss, author of A Universe From Nothing. Canada has been deeply involved in the LHC project, investing $70 million in the accelerator, detector, and computing parts of the project; another $30 million in funding has gone to Canadian researchers, including 150 scientists on the ATLAS team. (Physicists on ATLAS come from 38 different countries.) TRIUMF is Canada's main link. It hosts a computing centre that processes raw data from particle collisions.

Even before the LHC smashed its first protons together, onlookers worried that its scientists were playing God—that recreating the Big Bang in a man-made machine could have catastrophic consequences, the kind we couldn't even imagine. Some thought the LHC would rip open a black hole, gobbling up our planet whole. In the novel *Angels & Demons*, by Dan Brown (who also penned *The Da Vinci Code*), a Harvard University symbologist named Robert Langdon tries to foil a secret society intent on bombing the Vatican with a canister of antimatter, stolen from CERN. Things started to get really strange in 2009, when two physicists, Holger Bech Nielsen and Masao Ninomiya, published papers suggesting CERN's project was doomed to fail—that the creation of the Higgs would be sabotaged by forces from the future, because the particle itself might violate the natural order.

CERN has done its best to counter these worries. An entire webpage is devoted to *Angels & Demons*, revealing that "portable antimatter traps," as used in Brown's fiction, wouldn't actually work in reality. Its page tries to put to rest any fear of destructive black holes: "Astronomical black holes are much heavier than anything that could be produced at the LHC." Still, the particle accelerator itself has attracted its share of crackpots, like a man arrested on the Swiss side in 2010, who claimed he'd travelled from the future to stop CERN from destroying the world.

It probably didn't help that in its early days, perhaps fuelling Nielsen and Ninomiya's theories, the LHC was accident prone. One of several shutdowns, in 2009, was blamed on a bird flying overhead. It had apparently dropped a piece of baguette into an electric substation, shorting out the power to the LHC's cryogenic cooling system—a major problem, because the accelerator is kept at a temperature colder than deep space.

The cost of the LHC—it's one of the most expensive scientific instruments ever built—has inspired another kind of protest. *Forbes* estimated that "the total cost of finding the Higgs boson ran about [US]$13.25 billion" and dubbed this "a bargain," but not everyone sees it that way. Abdel-Aziz told *Maclean's* that one of her teams is working on upgrades to the inner detectors of the LHC that would replace silicon with diamonds. "We know that diamonds are stronger than silicon," she explains. The image of scientists in Switzerland piecing together equipment made of diamond, at a time when the European continent is foundering financially, might yet prove controversial.

Back in December, when scientists announced they may have glimpsed the boson, excitement began to build; for Vincter, there were some tense months as she sensed they might be closing in. “We saw our range of Higgs space shrinking and as we took more data we’re hyperventilating, and then: boop. A little peak appears. And we’re like: YAY!” Vincter, fists clenched, does her best victory jig. For a while it was tough, says the scientist who’s spent 14 years at CERN, “to tell people: calm down, relax, do what you’ve always been doing.” In June, she watched her ATLAS team conclusively detect a Higgs-like particle—with a mass in the predicted range of 125-127 gigaelectronvolts, or GeV. (Indeed, the mass of the newly discovered boson has been pinned at about 125 GeV.) Vincter’s hopes of a decisive find were buoyed when, a couple of weeks before the July 4 announcement, “delicious rumours” swirled that CMS physicists had been spotted toasting each other with champagne.

Twenty-four hours after the big discovery was announced, CERN’s main lobby was swarming with tourists. Pilgrimages to the ’50s-era research site had begun and CERN appeared to be at the edge of a defining cultural moment. At reception, the calm Frenchman manning the information desk confirmed a spike in visitors. Weekend tours of CERN, he said, are now booked solid until early September. But it’s not just the quantity of tourists that has changed. He added: “There are tourists here now who otherwise would not be here. In French, we would call them, ‘*Monsieur et Madame tout le monde.’* ” In other words, the place is brimming with people, many of whom wouldn’t know a Higgs boson from a plain old quark.

With the LHC currently switched on, most areas are closed to tour groups. One building still open to visitors is ATLAS headquarters. Here, visitors can press their noses to the glass panel separating them from the “control room,” where Ph.D. students are permanently bent over laptops and multi-screened computers: monitoring the LHC’s detectors and performing regular checks. It’s important, David jokes, not to check Facebook when you are seated near the tourist entry. Large screens mounted on the back wall of the room flash reams of code and line graphs.

Higgs mania aside, some people are already asking—what can we do with a Higgs boson particle? What good is it? This isn’t unreasonable; when electromagnetism was discovered more than 100 years ago, for example, no one could have envisioned the role it would play in our global cellphone system today.

Some imaginative thinkers have a few ideas about the Higgs: temporarily “shutting off” a person’s Higgs field could enable them to travel at the speed of light (if they could figure out how to switch it back on again one they reached their destination), or teleport from one location to another. Maybe a *Star Trek* phaser-style weapon could be designed, to zap enemies into a bunch of swirling light particles. Of course, as Krauss noted in an interview with *Discovery News*, “turning off” a person’s Higgs field would involve heating them up to “something like a billion, billion, billion degrees.” And if we could do that, we’d probably be smart enough to find easier ways to dispatch our enemies, or get from point A to point B.

What’s far more exciting is what the Higgs boson will teach us, now that we can study it—showing a way forward beyond the Standard Model. Physicists are eager to build on that old theory, even push it aside, and the Higgs could show us how, shedding light on the next big questions in physics.

The same day the Higgs finding was revealed, another remarkable discovery was announced, to much less fanfare: a team of researchers managed to detect a filament of dark matter bridging two clusters of galaxies, the first time such a thing has been done. Dark matter is a mysterious substance about which almost nothing is known; its gravitational pull seems to hold galaxies together, like a massive skeleton. But we can't see dark matter; we only know it's there from calculations of the speed at which galaxies move.

The matter we know and understand accounts for just four per cent of the known universe; the rest is dark matter and dark energy. Now that the missing piece of the Standard Model is in place—the Higgs boson particle—scientists will be able to build new theories, new models, that might help explain the other, as-yet-invisible 96 per cent, about which we know almost nothing.

Two kilometres underground, in a mine near Sudbury, Ont., a team of scientists is looking for a hypothetical particle they believe could make up dark matter. "It's not because we think there's more dark matter in Sudbury," says Nigel Smith, director of SNOLAB. Rather, rocky Sudbury is a perfect place for scientists to work underground, shielding their instruments from the cosmic radiation that bombards Earth's surface. "For us, the Higgs discovery is really exciting," Smith says. "We're working on physics beyond the Standard Model. The fact that it's been validated with this missing piece gives us confidence that the next models aren't built on a bad foundation."

One of those hypothetical models is supersymmetry—or "SUSY," as it is fondly nicknamed at LHC headquarters—the idea that every known particle has a "superpartner," which we haven't yet found, and that dark matter is one of those superpartners. According to the supersymmetric theory, "you'd expect to see other Higgs bosons," says Gordon Kane, director emeritus of the Michigan Center for Theoretical Physics. (It was Kane who won that $100 bet against Hawking.) And so we might only be seeing half of the picture. The next big thing to come out of CERN might very well be another Higgs boson, or several. "If Mother Nature is boring, Mother Nature gave us the Higgs boson and nothing else," Vincter says. "But if Mother Nature is kind, then she'll provide us with more things to look for. And one of these things is another Higgs boson."

Observing particles to see how they behave might even take us down a path toward alternate, unexplored dimensions. There are four dimensions we all know of, including time; but there may be others, even seven or eight of them, theorists say, which none of us can access in our daily lives. "There's one idea, that at the Big Bang, all dimensions were the size of tiny particles," says Richard Teuscher, a physicist at the University of Toronto and an ATLAS team member who's based in Geneva. "And then some of them expanded, and the others never did." Kane compares it to a long, thin straw. "You can move along the straw; that's a big dimension. And you can move around the straw. But you're bigger in size than the straw, so you can't move to the dimension inside it." But particles can.

Take the graviton, a hypothetical particle that conveys gravitational force—scientists believe it could be constantly "leaking away" into other invisible dimensions, Teuscher says, because gravity is so weak. "Gravity seems so strong because it adds up over the huge scale of the Earth," he says. "But do an experiment: take a magnet and lift a paperclip. That magnetic force is stronger than gravity." Gravity might have most of its interactions in dimensions that are "curled up in tiny space you can't see," he says. And the Large Hadron Collider may find them.

The LHC is only running at roughly half its energy capability, Teuscher notes. Next year it will begin a shutdown period, getting ready to rev up again by 2014. By then, the Big Bang Machine will have finally reached its full power. There is hope it will reveal dark matter for the first time. "It could happen any time," says Vincter, smiling mischievously, "and I can tell you that a lot of people are working on it." But one of the first orders of business will be to study this new Higgs particle, "to make sure it really is the Standard Model Higgs, and not something that's fooling us," Teuscher says. "Maybe there's already some new physics there."

Even after chasing the Higgs boson for decades, many scientists are hoping that's the case—that what CERN has found isn't exactly the Standard Model Higgs boson, but something more exotic. "What's been observed appears to have the properties of the Higgs particle," Krauss says. "That's all we can say for now." Soon, we'll be able to say much more—and move on to the other unknowns.

To say CERN physicists wince when the phrase "God particle" is dropped would be an exaggeration, but they tend to have an opinion about it. Those opinions range from. "I'm a little bit annoyed when people use it" (Vincter), to, "Are you going to use 'God particle' in your article!? I hate it" (Abdul-Aziz). These physicists are looking for answers to questions humankind has asked itself for millennia—who we are, where we came from, why we're here—but when it comes to some of the biggest existential riddles, they don't much want to talk about it.

Religion aside, physicists can't help but effuse about the Higgs boson particle, which they spent decades chasing, using the grandest of terms. "It's beautiful," Krauss says. "The fact that empty space is endowed with these properties—that what appears to be empty space endows particles with a mass. Apparently, nothingness is responsible for our existence." The fact that Peter Higgs and five others dreamed this up back in the 1960s is almost as remarkable. "Normally, experiment leads theory," Krauss continues. In this case, theory ran ahead by half a century.

Scientists at CERN allowed themselves a few moments to savour the discovery, but not much more. Behind enough concrete to drown out the outside murmur, they worked furiously toward publication. According to their long-ago-settled procedure, both the CMS and ATLAS teams agreed to publish their findings simultaneously: as side-by-side articles in the same academic journal. Each scientist (and there are thousands) will be listed as an author: alphabetically, so as not to politicize the process. The first surname to appear on ATLAS's paper will be "Aad." Vincter cautions, "even if we make it public, it's not final until it makes its way into a journal."

Savard is one of a small handful of editors on the ATLAS paper. More than two decades after beginning his quest for the Higgs boson particle, he's not letting himself get carried away. On the morning of July 4, after the results of the greatest hunt in the history of modern physics were announced, Savard took a moment to pass on quiet felicitations to colleagues—before heading back to work.

http://www2.macleans.ca/2012/07/17/the-higgs-boson-discovery-changes-everything/

Much ado about nothing

Written by: Cliff Burgess
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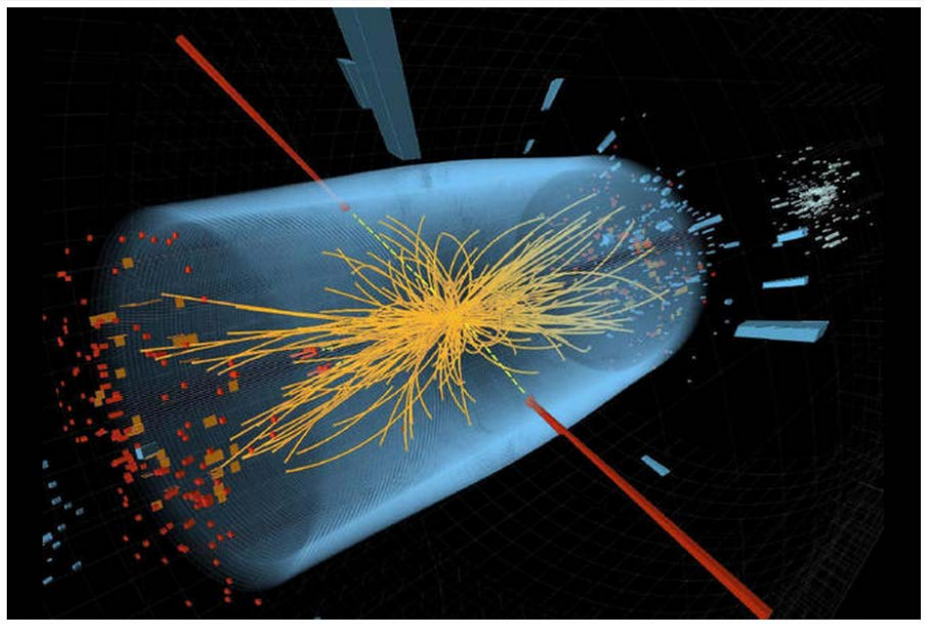
Discovery of the elusive Higgs boson tells us that the vacuum state is not empty – and that far-sighted investments in scientific research can pay off in unpredictable ways

Early Wednesday scientists at CERN, the international particle physics laboratory in Geneva, announced the discovery of the long-sought Higgs particle. This discovery culminates literally decades of effort by thousands of physicists and engineers spending billions of euros to build the Large Hadron Collider (or LHC).



An image proided by CERN shows the release of energy after the collision of two protons. Scientists at the world's biggest atom smasher claimed the discovery of a new subatomic particle on Wednesday, calling it "consistent" with the long-sought Higgs boson. AP PHOTO/CERN

So, are they now done? Was it worth the effort, given that the Higgs particle was predicted over 30 years ago by the Standard Model of particle physics, itself tested in many other ways over the intervening years? Is it all much ado about nothing?

I would argue yes, but perhaps not in the way one might think. Discovering the Higgs is indeed a Nobel-worthy Big Deal. But it is all about nothing: it is significant because of what it says about the vacuum.

Colloquially, a vacuum is a space entirely devoid of matter, but to physicists the vacuum is the physical state having the lowest energy. Until the 1960s these two notions of vacuum were thought to be synonymous. Since matter carries energy, when you remove it all what is left should have the least possible energy.

But over 40 years ago Peter Higgs and others realized that the state with least energy needn't be empty, it can instead be filled with a physical quantity called the Higgs field. A field is something that can mediate a force, much like the gravitational field mediates the attraction felt by a ball falling to the Earth or a magnetic field mediates the force between the Earth and a navigational compass. The hypothetical Higgs field would similarly mediate a new force between particles.

What is unusual about the Higgs field is that it costs less energy to have it than not to have it, so although gravitational and magnetic fields on Earth would vanish without our planet to act as a source, the Higgs field can be present even in the vacuum, without any particles. As such, it provides a ubiquitous environment through which all elementary particles swim, and so must be an important part of any understanding of their properties.

The idea that the vacuum is pervaded by a physical field seems very bizarre. Its proposal in the 1960s was provoked to reconcile some new-found properties of the weak interactions — those interactions that mediate radioactive decays — with familiar properties of elementary particles. In particular, the weak interactions appeared to require elementary particles like the electron to move at the speed of light, which it doesn't. But the puzzle could be resolved if a particle's interactions with the Higgs field in the vacuum could slow it down.

How could such a radical speculation be tested? What better way than to excite a wave in the vacuum. This is what CERN physicists have just done. By colliding particles with sufficient violence in the LHC, they have caused a wave to move through the vacuum. In the same way that electromagnetic waves (including light, radio and UV waves) are known to consist of swarms of particles called photons, the newly discovered Higgs particles make up waves in the Higgs field: that is, waves in the properties of the vacuum itself.

It has been an epic journey. After being out on a theoretical limb for more than 40 years, a pillar of experimental evidence now supports a radical view of the vacuum. And now that waves in the vacuum can be produced at will, their study can test whether the vacuum is better described by the Standard Model or by one of the alternatives that wait to replace it. Discovering a flaw in the Standard Model would be an even Bigger Deal.

Last week saw the first dividends from many far-sighted investments. These range from decisions by individual physicists to expenditures by universities, laboratories and funding agencies worldwide. Research in pure science can be a hard sell to an investor looking for a quick return. Yet many talented people, essential products and inspiring ideas are unexpectedly spun off from fundamental science.

Will the LHC affect our lives? In some ways it already has: the ability to reach the world at the click of a mouse is partially due to the invention at CERN of the World Wide Web in the early days of LHC development. In the long run, its long-term impact is difficult to predict. But if revolutions in computer miniaturization can be traced to our ability to manipulate atoms, imagine what an ability to manipulate the vacuum might bring. Much ado about nothing indeed.

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http://www.thestar.com/opinion/editorialopinion/article/1223002--higgs-boson-explains-a-lot-about-nothing