

# Information Drawn from the

## 2006 NSERC Review of Perimeter Institute

### Overview

This compendium of information relates to a Natural Sciences and Engineering Research Council of Canada (NSERC) assessment of Perimeter Institute for Theoretical Physics (PI) and includes data extracted from NSERC documentation and PI presentation materials.

The independent review took place during September of 2006, in accordance with all procedures, at the time an initial NSERC multi-year grant of five years earlier was reaching expiration.

The review process examined all aspects of the Institute, including scientific research and educational outreach activity, dating back to inception. The Review Committee also discussed and evaluated future plans for the next five years – in conjunction with PI's requested commitment of the Government of Canada to continue and increase funding in the order of \$50m which, with partnering investment from the Province of Ontario, would enable the Institute to compete internationally and be among the very best in the world.

The sections that follow include NSERC assessment criteria via the *Charge of the Committee*, the *Main Conclusions*, a *Summary of Select Findings* extracted from the review and *Detailed Information* drawn from the final report. Additional information includes PI's stated *Objectives* and *Related Achievements* to that point in time.

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# Charge of the Committee

## Review of the Perimeter Institute for Theoretical Physics

### Charge of the Committee

June 28, 2006

According to the Grant Agreement between NSERC and the Perimeter Institute for Theoretical Physics (PI), a formal evaluation of the past and planned activities of PI is required by NSERC. Under the aegis of NSERC, the review of PI is to be conducted by an international *ad hoc* Committee. The Committee is asked to carry out a thorough review of the achievements of the Institute since it launched its operations in 2001, and to evaluate its strategic and operational plans for the next five years. The Committee is to summarize its review and findings in a report, which must be submitted to NSERC no later than September 22, 2006. The report should represent the consensus of the entire Committee. NSERC will share the content of this report with Industry Canada, which might use it at its discretion for any appropriate needs or purposes.

The Committee members will be chosen for their expertise. The Committee will include highly regarded scientists from abroad and Canada. NSERC's guidelines with respect to conflicts of interest will be strictly applied. NSERC's Grant Selection Committees (GSCs) that serve disciplines covered by PI will be represented by ex-officio members. These are the Space & Astronomy, Subatomic Physics, and General Physics GSCs (17, 19, and 29, respectively). Moreover, the Major Resources Support GSC will also be represented by an ex-officio member. An NSERC representative will act as an observer during all phases of the Committee's review.

As part of the review, the Committee is asked to perform a thorough analysis of the past, current, and future research and outreach activities of the Institute, its operating and management structure, as well as its current operating budget and articulated financial needs. As part of the assessment, the Committee should address each of the following criteria:

- Quality, pertinence, and impact of the past, current, and planned scientific activities, and significance of the research themes (areas of discipline) to the related communities.
- Merit and excellence of the Institute's researchers and users.
- Extent to which the research activities of the Institute meet the needs and plans of the scientific communities that are related to PI's areas of research.
- Role and impact of the Institute on the advancement of the areas of research and, when applicable, on the dissemination and use of the generated knowledge in these areas.

- Extent and excellence of the contribution to the cutting-edge scientific training of Canadian highly qualified people, and to the attraction and retention of high-caliber researchers.
  - Appropriateness and effectiveness of the Institute's management structure and accountabilities. Excellence of the overall governance of the Institute.
  - Quality of strategic and operational plans of the institute for the next five years.
  - Demonstrated need for financial assistance, including the appropriateness of the requested resources, and extent of the commitment and support from universities, other private or public organizations, and users.
  - Effectiveness of the financial and budgetary control mechanisms.
  - Effectiveness of the public-private partnership model used to fund the Institute since its establishment.
  - Outputs and benefits generated by the Institute since its launch. Scientific and technological impact and extent of the return on the investment.
  - Demonstrated scientific and/or technological benefits to Canada. This includes a demonstrated contribution to the positioning of Canada at the forefront of knowledge creation, innovation, and competitiveness.
  - Synergy between existing private and public resources in the proposed areas of research, and depth of scientific and economic linkages between the Institute, the scientific communities in the research areas covered by PI, and institutional partners.
  - Collaboration with complementary Canadian or, if applicable, international institutions.
  - Ease of access to, and actual use of, PI's resources by researchers from related research communities in Canada.
  - Outreach activities to the scientific and academic communities in order to raise the awareness about the Institute, its research areas, its accomplishments, and the opportunities it offers.
  - Outreach activities to the broad public, in particular the youth, to trigger and sustain interest in science.
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# **Main Conclusions Drawn from Final Report of NSERC Review of the Perimeter Institute**

September 26, 2006

- PI has been a great success on a world-wide scientific scale, for Canadian science, and for education and outreach. A number of major research achievements can be attributed directly to the existence of PI. The Institute should be applauded for its success in attracting such high quality researchers.
- PI has outstanding management. It provides strong oversight while retaining the creativity and flexibility needed for a rapidly growing enterprise. PI's plans for the future are excellent and the Institute appears very well prepared to move ahead with its proposed plans for the next five years.
- We strongly support PI's request for government funding to its full extent and for a period of at least 5 years.

# Summary of Select Findings Drawn from Final Report of NSERC Review of the Perimeter Institute

## Research Related

- PI was founded just seven years ago, and since that time has developed an excellent international reputation as a leading center for some of the important areas of foundational physics.
- PI recognized early that the emerging area of quantum information was under appreciated by the general academic community, and was therefore a subject where a newly formed institute could have a large impact. Although it now seems that this was an obvious course of action, we must not forget that many strategies that seem obvious in hindsight actually require great insight to pursue.
- PI's activities in quantum information (QI) have helped place Canada at the forefront of the field internationally (and) a number of major research achievements in QI can be attributed directly to the existence of the Perimeter Institute.
- It is also responsible for bringing Raymond Laflamme to Canada and nurturing the resulting development of the Institute for Quantum Computing (IQC) at the University of Waterloo.
- In the area of quantum information theory it is likely that, in the not too distant future, there will be “real world” applications of the concepts and methods that are now being developed. The strength of PI in this area might provide Canada with technical expertise of significant economic importance.
- The committee notes that, even in abstract fields like string theory, quantum gravity and foundations of quantum theory, there is a significant effort to make contact with experiment and observations. This is very important for any physics organization, but not always realized at those institutes focusing on theory.
- (Regarding Sting Theory) the choice of faculty has been excellent, producing a remarkably balanced research effort, and Perimeter should be applauded for its success in attracting such high quality researchers.
- The Quantum Gravity group is internationally renowned, and often referred to as the pre-eminent group in this field.

- (Regarding Particle Physics) the associates and visitors are of very high caliber (and) it hopes to become a leading centre in this area during the next five years.
- In a small field like Foundations of Quantum Theory (also known as Quantum Foundations), the PI group has rapidly become a reference, and we expect it to increasingly play this role in the future.
- (Regarding Cosmology) it is particularly fortunate that, with Paul Steinhardt as the Director of its Scientific Advisory Committee, PI has the expertise of one of the world's most eminent cosmologists at its disposal (and) the plans of PI to develop a strong and focused activity in this area are timely and very well justified.

## **Outreach Related**

- It is the committee's assessment that the outreach component of PI is making a highly valued contribution to the public understanding of theoretical physics and participates in the contributions of physics, and science generally to culture.
- In a society and economy increasingly dependent upon the fruits of science, the value of educating Canadians—adults, young people and leaders—about science itself and the credibility and beauty of science and the scientific method cannot be overstated.
- The panel appreciates that PI has applied the resources and expertise required to strongly launch each outreach product and then build and sustain the success of each product.

## **Management Related**

- The Institute is consistently applying the best practices of strategic management in a not-for-profit context.
- The Scientific Advisory Committee, an expert group of distinguished physicists, is an important resource to both Board and management in assuring that strategic plans are well informed and well grounded in the field.
- Given the past success and the depth of the observed best practices, PI is very well prepared to move ahead plans for the next five years.

## Budget Related

- Given the nationally and internationally important role played by PI in building Canada's leadership in science and that it is a vital national resource for Canadian researchers and institutions; the panel strongly supports PI's request for government funding to its full extent and for a period of at least 5 years.
- ...it is important that the funding be as stable as possible over a period not less than five years. This will give it the flexibility it needs to grow without compromising on faculty quality.
- During this five year period Ontario and Canada may wish to consider how to increase their research funding envelopes to accommodate the Institute's needs beyond 2012 as part of the regular research funding process.

## Canadian Impact Related

- It is clear that PI has established the nucleus of a world class group with the ability to attract first class researchers from around the world.
- PI (has) had a tremendous and positive impact on the training of highly qualified personnel beyond the local area, bringing together researchers from across Canada and around the world.
- It is clear that the primary economic benefit arising from activities at PI is the training of the best and brightest Canadian minds.
- While some of these will pursue academic careers in physics, the vast majority will apply their analytic and technical skills outside of the physics research environment (and) it seems clear that in the long run this will make Canada more competitive.
- The 21<sup>st</sup> century is the information age. Access to highly trained people will dictate how competitive a country will be in the long run. Foundational theoretical physics is one of the least resource intensive areas of exploration at the frontiers of knowledge. Thus, it provides an especially cost-effective way to stay at the forefront of one of the most cutting-edge fields of science. In this sense, support for PI is a very efficient use of resources to foster a group of world class researchers in Canada and train Canadians in this information age.
- These payoffs, not only in areas such as quantum information technology but also in gaining a more fundamental understanding of the mechanisms underlying gravity, could be enormous.
- One can already see a number of spin-offs into the local community (primarily through the PI's outreach and cultural programs).

## Concluding Remarks and Recommendations

- In a very short period of time, Perimeter Institute has grown from nothing to an important international center for theoretical physics.
- PI is very visible on the international scene, having hosted some of the key international conferences.
- It has vibrant educational and outreach programs that have enriched the local community and are also of national and international scope.
- The public-private partnership model used to fund the Institute since its establishment has proven extremely effective.
- To be frank, the committee is amazed by the success that PI has had over the last few years.
- Given the great success of PI and the strong support it receives from the private sector, we recommend that Canada's federal government continues to provide strong financial support to Perimeter Institute and be an active partner of this successful and promising enterprise.

# Detailed Information drawn from 2006 NSERC Review of Perimeter Institute

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# Committee Members

September 26, 2006

Mark Wise-Caltech (Chair)

Andrew Cohen-Boston University

Arthur Hebecker-Heidelberg University

Gerard Milburn-University of Queensland

Bill Peters-TELUS World of Science / Calgary

Carlo Rovelli-Université de la Méditerranée / Marseille

John Smolin-IBM

William Trischuk-University of Toronto and Institute of Particle Physics

Lynann Clapham\*-Queen's University (Representing the Major Resources GSC)

Alan Coley\*-Dalhousie University (Representing the Space and Astronomy GSC)

Harold Haugen\*-McMaster University (Representing the General Physics GSC)

Byron Jennings\*-TRIUMF (Representing the Subatomic Physics GSC)

\* Ex-officio member.

## Procedure

The committee met on September 6-7, 2006 at Perimeter Institute for Theoretical Physics (PI) and performed an in-depth review of PI's past accomplishments and future plans. Presentations were made by Research Faculty, the Executive Director Howard Burton and the Director of Scientific Outreach, Damian Pope. The committee also met with the Chair of the Scientific Advisory Committee, Paul Steinhardt, several members of Perimeter Institute's Board of Directors, and with some postdoctoral scholars and graduate students. In addition, informal discussions with members of PI and its Board of Directors occurred during a lunch and a dinner on the first day of the meeting. The committee had several in camera discussion sessions where conclusions were drawn. A closing session, where the committee's conclusions were summarized in an oral presentation to PI's participants occurred at the end of the meeting. Following the meeting, the committee members corresponded via email and drafted this report.

## Summary

### Main Conclusions

- PI has been a great success on a world-wide scientific scale, for Canadian science, and for education and outreach. A number of major research achievements can be attributed directly to the existence of PI. The Institute should be applauded for its success in attracting such high quality researchers.
- PI has outstanding management. It provides strong oversight while retaining the creativity and flexibility needed for a rapidly growing enterprise. PI's plans for the future are excellent and the Institute appears very well prepared to move ahead with its proposed plans for the next five years.
- We strongly support PI's request for government funding to its full extent and for a period of at least 5 years.

### General Summary

PI was founded just seven years ago, and since that time has developed an excellent international reputation as a leading center for some of the important areas of foundational physics. Their most developed groups are in quantum information theory, quantum gravity and string theory. In addition they have smaller, but high-caliber, groups in foundations of quantum mechanics and cosmology, and a nascent effort in theoretical particle physics. At the present time particle physics is not represented by any permanent faculty at Perimeter, but only through associates and visitors. Developing world class research groups in some of the most important areas in theoretical physics over such a short period of time is a remarkable accomplishment. They have also developed a highly successful and very creative outreach program that inspires and educates pre-college students and high school teachers in science, and includes a highly successful lecture series for the general public.

It is PI's intention to grow its efforts in foundational physics over the next five years, resulting in a doubling of the faculty and postdoctoral scholars at PI. They hope in this process to greatly strengthen their efforts in foundations of quantum theory, cosmology and particle physics. Given their exceptional track record we think that this ambitious goal is realistic and recommend enthusiastically that PI continue to be strongly supported by Canada's federal government.

PI recognized early that the emerging area of quantum information was under appreciated by the general academic community, and was therefore a subject where a newly formed institute could have a large impact. Although it now seems that this was an obvious course of action, we must not forget that many strategies that seem obvious in hindsight actually require great insight to pursue. The associates program, in which high caliber scientists commit to spending at least three months of the year at PI, played a crucial role in this success. It helped strengthen the effort at the University of Waterloo, that now has a center for quantum information and quantum computing (the Institute for Quantum Computing, IQC). Together, PI and IQC (which includes some PI associates) make the Waterloo area one of the premier sites for quantum computing, capable of competing for the best postdocs, faculty and visitors in the field.

Reconciling gravity with quantum mechanics is one of the most widely recognized foundational issues in modern theoretical physics, and it is appropriate for PI to have a strong presence in this area of study. String theory, providing a unified framework for quantum gravity along with the other forces of nature, is one of the core areas of modern theoretical physics and is strongly supported by the university system, theoretical institutes and national laboratories. Other approaches for quantizing the gravitational interaction such as loop quantum gravity are less widely supported. PI has a strong, world-class effort both in string theory and loop quantum gravity, as well as an active involvement in other approaches to quantum gravity. This is consistent with PI's philosophy of supporting both orthodox and unorthodox approaches to foundational questions. Quantum gravity is an especially appropriate area in which to adopt this philosophy. For example, it was not that long ago that string theory was studied by only a few theorists. Although they were considered to be talented scientists working on a subject of great importance, most judged that the chances of significant progress were at best marginal. It is particularly impressive that in an area like string theory, where competition from the university system and other international centers for the best researchers is fierce, PI has nevertheless been able to build up a strong effort.

Even though PI is a center for theoretical physics, the committee notes that, even in abstract fields like string theory, quantum gravity and foundations of quantum theory, there is a significant effort to make contact with experiment and observations. This is very important for any physics organization, but not always realized at those institutes focusing on theory. Without it, PI would risk becoming a center for mathematics rather than foundational issues in theoretical physics. In the area of quantum information theory it is likely that, in the not too distant future, there will be "real world" applications of the concepts and methods that are now being developed. The strength of PI in this area might provide Canada with technical expertise of significant economic importance.

PI has one member of its faculty studying foundations of quantum theory and another one working on cosmology. Foundations of quantum theory, like non-string

theoretic approaches to quantum gravity, is an area with limited support in the university system. However it has strong overlap with quantum information theory, quantum gravity and cosmology, and it is certainly desirable that PI has a significant presence in this area. The last few years have seen a revolution in cosmology: observations have improved our knowledge of the universe on large distance scales, and this new knowledge has given rise to new theoretical challenges. There is no doubt that this area will remain essential to foundational physics. Like string theory, it is a branch of theoretical physics where competition from the university system will make developing a world class effort able to attract the best postdoctoral scholars and visitors challenging. Historically, constructing ever higher energy accelerator experiments has been the primary method employed to explore the nature of the strong, weak and electromagnetic interactions at a fundamental level. A new era of great discovery may be nearing as the large hadron collider at CERN (LHC) prepares to take data. At present, PI has no faculty in elementary particle theory but it hopes to become a leading center in this area during the next five years.

PI is active in education through classes taught by the Institute's faculty and associates, and through meetings and conferences hosted and organized by PI. These efforts have been very successful, and PI has hosted some of the key meetings in several fields. Although meetings are an important way for PI to gain visibility and an excellent service to the scientific community, it is important that conferences and workshops not prove too much of a distraction for the faculty away from their primary research. Ultimately the most important measure of success for PI will be the quality of research done by its faculty, associates, postdoctoral scholars, graduate students and long term visitors.

Developing world class groups in cosmology and particle theory will be at least as difficult as in string theory. PI should not shy away from unconventional methods (e.g. group hires) as it attempts to grow. Furthermore, PI should not view an inability to fully develop these areas over the five year time horizon as a failure. Attracting senior faculty and top junior faculty candidates in these areas is notoriously difficult and PI may have to endure several rounds of declined offers before they have success. However, the committee would view any compromise on the quality of the candidates it considers in order to quickly grow in these areas as a failure.

Over the next five years, PI intends to double its faculty and postdoctoral scholars to fully develop programs in the areas mentioned above. In addition to requiring additional funding for this expansion in personnel, an expansion in space will also be necessary. We did notice a special atmosphere that PI has: interactions between different groups are frequent and fruitful\*. This character will be difficult to preserve as the Institute grows and we hope that special care will be taken to safeguard it. Even if the number of PI faculty and postdoctoral scholars does not grow as rapidly as planned, significant capital expenditures (for the required expansion in space) are likely to occur over the next five years and the requested funding can be put to good use.

We feel that it is reasonable that PI grows its endowment until it reaches a

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\* For example, methods from quantum information theory have recently been applied to discover new conserved quantities in an approach to quantum gravity.

stable faculty size and is able to fund its operations partly through government grants and partly from interest on the endowment. Given PI's ambitious goals and the uncertain time line for growth of its faculty, it is important that the funding be as stable as possible over a period not less than five years. This will give it the flexibility it needs to grow without compromising on faculty quality.

PI has a very effective management structure. It has developed as the Institute has grown. In addition to the Executive Director Howard Burton, there is now a Chief Operating Officer, a Director of Communications and a Managing Director of Outreach Programs. There is also a Scientific Advisory Committee (SAC), which advises the Board of Directors and the Executive Director on matters of scientific policy, appointments and renewal of scientific staff. At the top of the management structure is a Board of Directors that has considerable expertise in corporate and university management. Managerial expertise and mentoring from the private sector through the Board has significantly contributed to the success of PI. Thus the private sector contribution goes beyond the large financial contribution. We feel confident that as PI continues to grow, the Board of Directors will ensure that the management structure remains tuned to PI's needs.

We considered the question of whether a Scientific Director with extensive research credentials was necessary. The success of the existing programs owes much to the efforts of the Executive Director. Howard Burton's drive and commitment to the process has been crucial to PI's past success and will continue to be crucial in the future. We do not recommend distancing him from the hiring process by the appointment of a Scientific Director, but recommend that the Institute remains flexible in its administrative structure as it grows.

Part of PI's mission is outreach: the education of the general public and pre-college students to improve understanding of the physical world. This is a particularly important goal given that science and technology plays such an important role in modern life. In addition to enriching individuals' lives, outreach targeted at pre-college students will lead to a more capable workforce and outreach for the general public will lead to better decision making at the corporate and government level. PI has been remarkably successful in these areas. Even after a year, its monthly lectures continue to draw audiences of around five hundred attendees. Its education programs for students are carefully crafted and well attended. PI continues to explore ways to construct programs that specifically engage women and minorities, and encourage members of these under-represented groups to enter scientific careers.

## **Research**

### **Quantum Information Theory**

The Quantum Information Theory group includes two faculty (Daniel Gottesman, Michael Nielsen), four associates (Richard Cleve, Raymond Laflamme, Michele Mosca, Ashwin Nayak), five postdocs (Jonathan Barrett, Matthew Leifer, Carlos Mochon, Robert Raussendorf, Danny Terno), one long term visitor (Alexandre Blais) and one graduate student.

PI's activities in quantum information (QI) have helped place Canada at the forefront of the field internationally. Starting from a very small base in theory and

experiment only a few years ago, Canada now has one of the largest national efforts in quantum information in the world.

PI has seeded this development of QI in Canada through first-rate faculty appointments, postdocs and strategic associate staff appointments. It is also responsible for bringing Raymond Laflamme to Canada and nurturing the resulting development of the Institute for Quantum Computing (IQC) at the University of Waterloo.

A number of major research achievements in QI can be attributed directly to the existence of the Perimeter Institute. One of the most exciting is the developing programs at the interface between QI and quantum gravity. This is unique, highly innovative and likely to have lasting and significant impacts on both fields. Already, we have seen new results in loop quantum gravity inspired by the tools and techniques of quantum information.

Work on topics more directly related to quantum computation has been carried out both by PI faculty and associates, especially those with joint appointment at the IQC. This close collaboration of a large group of researchers has led to progress on a new class of quantum codes (operator error correction) and an improved understanding of the vitally important (if practical quantum computers are someday to be built) threshold for fault-tolerant quantum computing. There is also ongoing work on new types of quantum algorithms (for example, search by quantum walks) and quantum cryptographic topics (secure computation, practical quantum key distribution).

One area that has not yet been developed in this remarkable build up of capability in quantum information is the link between QI and condensed matter physics. A condensed matter program at PI may lead to research collaborations mirroring the productive links between quantum gravity and QI. There have been some exciting developments in foundations of many body quantum theory and QI that are having a significant impact on the field (for example, connections between density matrix renormalization group and quantum information theory). If an opportunity to make a first rate appointment in this area does arise, we believe it should be grasped.

PI has also had an impact on graduate education in the surrounding universities. Access to international leaders in the field gives local PhD students a wonderful opportunity to participate at the highest levels in QI. The new course on Quantum Foundations developed by Ray Laflamme and others gives a good example of how the resources of the Institute can be leveraged to provide unique opportunities for local graduate students. Further development of these innovative teaching initiatives should be encouraged and a means found to share the results with more Canadian universities.

Ideas from quantum information theory have reinvigorated the field of quantum foundations. Taking an informational viewpoint gives a fresh perspective on old questions and PI is well positioned to exploit these connections with its program on foundations of quantum theory. An exciting example of the work at PI at the interface between quantum information and foundations is the “toy model” (based on

classical mechanics with restricted availability of information) which recovers many, but not all, features of quantum theory, thus more clearly delineating what is novel and needs explaining in quantum theory. It is likely that synergies will develop between the foundations, quantum information, quantum gravity and cosmology groups, as has happened with those groups already in place.

## **Foundations of Quantum Theory**

The Foundations of Quantum Theory group includes one faculty (Lucien Hardy), five postdocs (Alexei Grinbaum, Owen Maroney, Ward Struyve, Hans Westman, Samuel Colin) and five long term visitors (Jeffrey Bub, Paul Busch, Joy Christian, Rafael Sorkin and Antony Valentini).

The establishment of quantum theory as the most effective description of the physical world during the first third of the 20<sup>th</sup> century was accompanied by an intense debate on the meaning of the physical and philosophical content of the theory. The immense phenomenological success of the theory, the urge to apply it to increasingly vast natural domains (atoms, nuclei, particles, condensed matter, plasma, lasers, neutron stars, etc.), as well as the dominant pragmatic philosophical mood of the second half of the 20<sup>th</sup> century, have left this debate in the background. As a technique to compute outcomes of measurements performed with physical apparatuses considered classical, quantum mechanics can be viewed, and has been viewed by a generation of physicists, as un-problematic. More recently, however, an increasing number of physicists have begun to face the intrinsic incompleteness of this way of describing nature (apparatuses are themselves quantum systems, after all), often pushed by the conceptual problems raised by the development of fields such as cosmology, or quantum gravity, where the pragmatic attitude mentioned above finds itself quite strained. The debate on the foundations of quantum mechanics has therefore resurfaced.

This is a very positive development: today, facing major conceptual problems such as those raised by seeking a quantum theory of spacetime, or describing the quantum physics near the initial cosmological singularity, theoretical physics can no longer rely on the pragmatic attitude that has been so effective over the course of the past hundred years.

Among the achievements of the group, is the proof that any hidden variable theory must have an infinite number of possible values; the definition of probabilistic theories with indefinite causal structure (a development that could have hardly happened elsewhere than PI); and an intriguing investigation of possible observable cosmological effects of the Valentini's version of the De Broglie-Bohm theory (which testifies to the attention to empirical verifiability that characterizes PI's theoretical research). In a small field like Foundations of Quantum Theory, the PI group has rapidly become a reference, and we expect it to increasingly play this role in the future

The interests of the group cover a diversity of approaches and research directions (information theoretic approaches, hidden variable theories, dynamical collapse

models, foundational problems raised by quantum gravity), including a marked attention to the possibility of empirical verification of ideas and theoretical proposals (testing violations of quantum theory in the early universe, testing local causality using EPR-Bell setup, testing Diosi-Penrose gravity induced collapse).

The group plays an important role inside PI and in the international scientific environment. At present, the group relies strongly on long term visitors to achieve an effective size. It would obviously find a more stable and effective configuration with a larger number of faculty.

## **String Theory**

The String Theory group currently consists of three faculty (Robert Myers, Jaume Gomis and Freddy Cachazo), one associate (Alex Buchel), six postdocs (Sujay Ashok, Evgeny Buchbinder, Xiao Liu, Christian Romelsberger, Nemani Suryanarayana, Andrei Starinets), one long term visiting faculty member (Amihay Hanany), a number of visiting postdocs and five (or six) graduate students. This is a large group, and the publication output has been correspondingly large. The research topics are quite diverse, including string phenomenology, quantum gravity and blackholes, and string theoretic techniques applied to gauge field theories. There are two especially noteworthy features of the string theory effort at Perimeter. Firstly, it has a strong phenomenological character. The committee was impressed that so much of the string theory research (as well as other Perimeter research areas) has focused on subjects with experimental and practical implications. For example, Rob Myers' work on cosmic superstrings has potential implications for observational cosmology; Jaume Gomis' work on the open string landscape may have application in the construction of realistic low-energy string models; and Freddy Cachazo's work on loop amplitudes in gauge field theories may find application in calculations relevant for the LHC. Secondly, the research often has been informed by results from other efforts at Perimeter, notably the quantum gravity and quantum information groups. For example, some of the work on black hole physics has incorporated ideas developed by researchers in quantum information.

It is also worth pointing out that this is an especially accomplished group in view of its youth. The initial appointment of Rob Myers, well-known for his seminal work on the physics of coincident D-branes, 5 years ago laid the foundation for strong string effort. Following the recent appointments of Jaume Gomis and Freddy Cachazo in the fall of 2004 and spring of 2005 respectively, the group has coalesced into a cohesive whole, while demonstrating substantial breadth. The committee is also impressed at the ability of the group to sustain such a high level of activity with only three faculty. They have achieved this through judicious use of their programs of associates, long term visitors, along with the large number of postdoctoral fellows.

One measure of the quality of this group is the ability to attract excellent postdocs, which they have done consistently over the past few years. In addition, they have hosted some of the world's best string theorists as part of their visitor program. This has allowed them to become a significant destination for string theory

research with only a modest faculty. The quality of these visitors is a testament to the rapid success of the Institute in string theory. They have also helped publicize their efforts by hosting numerous conferences and workshops.

The expansion of the faculty last year to three is an important step in ensuring that Perimeter establishes its own premier in-house research program with its own identity. The choice of faculty has been excellent, producing a remarkably balanced research effort, and Perimeter should be applauded for its success in attracting such high quality researchers.

## **Quantum Gravity**

The Quantum Gravity<sup>†</sup> group is internationally renowned, and often referred to as the pre-eminent group in this field. It is composed of three faculty (Laurent Freidel, Fotini Markopoulou and Lee Smolin), one associate (Thomas Thiemann), nine post-docs (Michele Arzano, Sundance Bilson-Thompson, Yujun Chen, Bianca Dittrich, Sabine Hossenfelder, Richard Etera Livine, Catherine Meusburger, James Ryan, Simone Speziale), one long term visitor (Kirill Krasnov), nine graduate students, and numerous other visitors.

The interest of the group is centered around the approach to quantum gravity known as “loop quantum gravity”, currently the most developed alternative to string theory. It covers all major aspects of this approach, from its canonical formalism, to its covariant “spinfoam” formulation; from the exploration of the possibility of naturally incorporating matter, to the low energy limit of the theory. The group also studies a number of other ideas and approaches to quantum gravity, including twistor theory, causal sets, and dynamical triangulations. This openness to unorthodox ideas makes PI a uniquely vital and bubbling research center.

The group has produced an impressive number of results and ideas that have marked the development of the field. Among the numerous scientific results, the committee notes the derivation of a phenomenological effective theory, where a deformation of the Poincaré group is realized, from full quantum gravity in 2+1 dimensions; this result ties together very different research directions in quantum gravity, possibly including an important indication on the possibility of studying its phenomenology. We also remark on PI’s contribution to the proof of a key uniqueness theorem, the “LOST” theorem, that puts loop quantum gravity on firmer mathematical ground, and the recent computations of the quantum gravitational corrections to the graviton propagator. Finally, we mention a recent notable idea for a derivation of the matter content of the standard model from the braiding of the quantum gravitational spin network states of loop quantum gravity. This is for the moment a highly speculative idea, but should it be supported its importance would be major.

The Quantum Gravity group plays a pivotal role in PI, since it has vital interactions with all the other groups. A close net of collaborations with members of

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<sup>†</sup> We use this term to refer to approaches, other than string theory, to the problem of quantizing gravity.

the Quantum Information group has developed, and concepts used in quantum information have also proven useful in quantum gravity. This is a remarkable development that has been made possible by the special character of PI's research environment. The interaction is also strong with the small Foundation of Quantum Mechanics group, motivated by numerous overlaps between the problems faced by these two areas. Tentative applications of loop quantum gravity to cosmology ("loop cosmology") are already well developed, and it is likely that the group will be able to develop a constructive interaction also with a future cosmology group at PI. This synergy is scientifically important, since cosmology might be the best ground to test any tentative quantum theory of gravity.

But the committee has particularly appreciated the cordial and constructive dialog between the String and the Quantum Gravity groups. String theory and Loop Quantum Gravity are alternative (tentative) answers to the same problem, which is one of the major open problems in fundamental physics; the debate between the two camps—strings and loops—is sometimes fierce. The relation between the String and Loop groups at PI, however, is marked by a reciprocal attention and respect which, while not diminishing the intensity of the debate, provides a scientifically productive climate, and opens the way to mutual understanding and cross fertilization. The committee views this relationship as a very positive realization of PI's Mission Statement to "create a lively and dynamic research atmosphere where many approaches to fundamental questions, both orthodox and unorthodox, are pursued simultaneously".

The senior member of the group is Lee Smolin, one of the scientific founders of PI. His ideas have often been controversial, attracting large interest but also strong criticism. But Smolin is clearly a major force behind the diversity, the intellectual vitality and the vibrant scientific atmosphere of PI. The committee notes with appreciation the recent hiring of Laurent Freidel, one of the most brilliant researchers in quantum gravity among the younger generation. The solid mathematical rigor of the research style of Freidel and Thiemann appropriately balance Smolin's and Markopoulou's creativity, resulting in a balanced research group.

The size of this group, the variety of the scientific interests, the number of postdocs and visitors make the group an international focal point for the field. The group is indeed clearly the first choice for most postdocs and junior scientists in the field.

## **Cosmology**

The Cosmology group at PI has one faculty member (Justin Khoury), five post-docs (Federico Piazza, Stefan Hofmann, Constantinos Skordis, Andrew Tolley, Mark Wyman) three long term visitors (Malcolm Fairbairn, Richard Holman, Joao Magueijo) and two graduate students.

Due to very significant observational advances in the recent past and because of expected future progress, cosmology and astro-particle physics are taking an ever

more central role in modern fundamental physics. On the theoretical side, the increased interest in cosmology is related to the puzzles of dark energy and dark matter, which have become more and more pronounced, as well as to the hope of testing very high energy scales or even quantum gravity effects through cosmological observations. In view of the above, the plans of PI to develop a strong and focused activity in this area are timely and very well justified.

Indeed, cosmology has already played an important role in PI's research activity in the past. Particularly noteworthy work in this context includes the analysis of "Warped reheating" by Cliff Burgess (associate) and collaborators and the opening of the new research direction of "Fundamental cosmic strings" by Rob Myers (faculty) and co-authors. Furthermore, important contributions to the theory of inflation and cosmological perturbations were made by Robert Brandenberger during his stay as a long-term visitor. The interplay of quantum gravity and cosmology has played a crucial role in the work of Lee Smolin (faculty). Also important is PI's organization and support of related workshops and summer schools over the past several years, such as the Summer School on Strings, Gravity and Cosmology and the Workshop on Cosmological Frontiers in Fundamental Physics.

More recently, with the successful hire of the young and very promising scientist Justin Khoury, PI has begun to build a dedicated research group in cosmology. Justin Khoury, who is already well-known for his early work on the "Ekpyrotic universe," has recently introduced new ideas on the dynamics of dark-energy scalars as well as in neutrino astrophysics and string gas cosmology. This general research direction has the potential to connect string-theoretic and quantum-gravity research, which are already very strong at the Institute, with cosmology and astro-particle physics. Further hires developing this area at the highest possible level, in line with the aims of PI, are strongly supported. The search for candidates with broad interests, who can strengthen the spirit of the Institute by enhancing interactions with other faculty members, is especially encouraged. In this context, it is particularly fortunate that, with Paul Steinhardt as the Director of its Scientific Advisory Committee, PI has the expertise of one of the world's most eminent cosmologists at its disposal.

## **Particle Physics**

The Particle Physics group consists of two associates (Cliff Burgess, Maxim Pospelov), two long term visitors (Gia Dvali, Victor Novikov) and one graduate student. At present, there is no faculty member at PI in particle theory and a viable effort cannot persist over the long term without one. It should be noted, however, that Freddy Cachazo's research on using methods from string theory to predict LHC backgrounds is actually particle physics (that makes use of string theory tools) and that Rob Myers' work on cosmic strings in string theory is the type of research that particle theorists are interested in. The associates and visitors are of very high caliber. Gia Dvali is a superstar and very well known for his work on using large

extra spatial dimensions for solving the hierarchy puzzle.

PI would like to expand their research group in elementary particle theory, and will have to do so if they are to have one of the top groups in this field. As was already mentioned, attracting very high caliber faculty to PI in this area is crucial to its success. This will not be easy as the turn on of the Large Hadron Collider (LHC) in the near future has heightened interest in this field.

## Outreach

It is the committee's assessment that the outreach component of PI is making a highly valued contribution to the public understanding of theoretical physics and participates in the contributions of physics, and science generally to culture. In a society and economy increasingly dependent upon the fruits of science, the value of educating Canadians—adults, young people and leaders—about science itself and the credibility and beauty of science and the scientific method cannot be overstated.

The level of commitment to this effort is demonstrated by the defined component of the PI budget devoted to outreach and the high level of these programs in PI's organizational structure. The total budget for these programs is comparable to that of some of Canada's small to mid sized science centers.

The programs used to launch and sustain the outreach effort over the past seven years, including lectures, classroom extension, teacher's workshops, student summer camps and public events, are appropriate and effective. The type of outreach products ranges from those that build awareness in a broad audience (like events and lectures), to those that offer in-depth engagement (like the teacher's workshops and summer camps for high performance students). This range of programming is appropriate to PI's objective to, *"Develop and maintain a vigorous public outreach program geared to Canadians of all ages to promote the excitement of fundamental inquiry and scientific discovery"*. The Institute is a leader in providing access to its events over the Internet, and making effective use of the Internet to complement and extend its outreach. PI's work to garner evaluative information from participants in order to learn how to improve programming is laudable.

The review committee endorses PI's view that outreach needs to remain focused and well supported. The panel appreciates that PI has applied the resources and expertise required to strongly launch each outreach product and then build and sustain the success of each product. Suggestions regarding connecting with the broader Canadian Outreach community were met with enthusiasm, and ways to facilitate this interaction were discussed informally with PI's Outreach Director.

## Management

PI is constituted as a not-for-profit corporation governed by a volunteer Board of Directors. The business model is corporate with the Board establishing policy and monitoring performance against policy and budget. The Board composition includes

six members with strong corporate and/or government leadership backgrounds and two with distinguished careers in academia. Board policy is implemented by the Executive Director, Howard Burton, effectively the Chief Executive Officer.

While the not-for-profit corporate model is less familiar on the Canadian academic research scene, it is a model that has proven robust and successful in related contexts, for example, among Canada's museums. This model has the capacity to bring about and manage significant change. In this model, the key to the effective development of, and execution of, corporate strategy is the cohesion with which the Board Chair, the CEO and the Board as a whole function together. The panel was able to assess this cohesion in two ways:

- The evident rapport of the Executive Director and the Board Chair, in presentations to the panel.
- The evident success achieved by the Institute during its first seven year strategic implementation cycle.

The quality of thought given to the strategic plan is another significant success factor. The Scientific Advisory Committee, an expert group of distinguished physicists, is an important resource to both Board and management in assuring that strategic plans are well informed and well grounded in the field.

In summary, the Institute is consistently applying the best practices of strategic management in a not-for-profit context. Additional best practices of note at PI include:

- Applying funds in a manner consistent with the stated strategic directions.
- Recognizing that building financial sustainability is a key long-term success factor.<sup>‡</sup>
- A strong, involved Board, with diverse leadership backgrounds.
- Board members acting as coaches and advisors to the CEO.
- An engaged CEO with strong leadership abilities and expert field-specific knowledge and contacts.
- Access to high quality information about the industry and the business environment.<sup>§</sup>
- The courage to initiate and carry out projects or practices that run counter to current or past practices, when it makes good sense to do so to achieve the goals.
- The courage to admit what is unknown and the evident fortitude to deal with those unknowns as they arise.

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<sup>‡</sup> The Institute is acting on this by building the endowment and soliciting funds from more than one source.

<sup>§</sup> Via the Scientific Advisory Committee and CEOs industry contacts.

Given the past success and the depth of the observed best practices, PI is very well prepared to move ahead with its proposed plans for the next five years.

## **Budget**

PI visualizes growing its operating budget (non-capital) from 2006 to 2012. Over the period, it plans capital costs. These costs are primarily related to capital repair, maintenance and upgrade of the two current buildings. It recognizes the need to plan for and fund additional capital in this time period to expand researcher and staff accommodation.

To provide for long-term financial sustainability, the Institute plans to increase its endowment. The important, extraordinary, leadership gifts of Mike Lazaridis, and those of Doug Fregin and Jim Balsillie, provide the basis for this endowment.

The Government of Canada's contributions have been over and above the funds otherwise available to researchers across Canada via the regular NSERC granting process.

The planned amounts and proportions are reasonable to fund the Institute's planned growth. During this five year period Ontario and Canada may wish to consider how to increase their research funding envelopes to accommodate the Institute's needs beyond 2012 as part of the regular research funding process.

Given the nationally and internationally important role played by PI in building Canada's leadership in science and that it is a vital national resource for Canadian researchers and institutions; the panel strongly supports PI's request for government funding to its full extent and for a period of at least 5 years.

## **Canadian Issues**

### **Training of Highly Qualified Personnel**

Although not an accredited degree granting institution, PI has had an enormous impact on the training of highly qualified personnel. From its summer programs for high school students and teachers (discussed in more detail as part of their efforts at "Outreach") through arrangements to provide undergraduate and graduate courses to students in the Kitchener/Waterloo area during the academic year, PI has had a significant and positive impact on the traditional higher education system in its immediate neighborhood.

Of course it has gone much further to build on the wealth of researcher talent assembled to address its research mission. The life blood of any research program is the availability of the best and brightest graduate students and postdoctoral researchers. The committee was very impressed with the quality, thoughtfulness and independence of the postdoctoral researchers. Those we met had been at PI for several years, and thus had played a role in shaping PI's postdoctoral culture. In only a few short years, a postdoctoral position at PI has changed from being seen as something of a gamble to being a prized position. The postdocs are given at least as much latitude to define their research program as would be the case at any of their peer institutions. In addition, they have access to resources that generously support

their travel to conferences and, even more importantly, to host workshops in Waterloo. One of the advantages they value most highly is the ability to host collaborators for medium term visits (ranging from a few weeks to a few months duration). Postdocs are among the most active and connected researchers in any scientific enterprise, and their ability to foster links with other research groups and cross-fertilize different research efforts has undoubtedly played an important role in the success of PI.

PI is also working on increasing its population of graduate students. While it does not provide any direct financial assistance for students, its research offerings act as a magnet for good students who might not otherwise consider studying in Canada. PI has made it possible to expand the graduate program at Waterloo beyond its traditional condensed matter base into the exciting new areas of string theory, cosmology and quantum information. Connections with the Institute for Quantum Computing at Waterloo provide additional leverage to expand the graduate student opportunities in the local area. While office space at PI is becoming ever scarcer as the resident staff grows, the committee hopes that PI will be able to preserve the ability to provide desks for graduate students, at least during the research intensive phases of their degree programs.

The many workshops and seminars offered by PI have had a tremendous and positive impact on the training of highly qualified personnel beyond the local area, bringing together researchers from across Canada and around the world. It seems clear that in the long run this will make Canada more competitive.

### **Scientific and Economic Benefits for Canada**

It is clear that the primary economic benefit arising from activities at PI is the training of the best and brightest Canadian minds. While some of these will pursue academic careers in physics, the vast majority will apply their analytic and technical skills outside of the physics research environment. This was probably one of the main motivations for the original industrial benefactors. It is too soon to quantify the economic benefits in this area, however, it is clear that PI has established the nucleus of a world class group with the ability to attract first class researchers from around the world.

One can already see a number of spin-offs into the local community (primarily through the PI's outreach and cultural programs). The timescale for traditional scientific and technological benefits will likely be measured in decades. These payoffs, not only in areas such as quantum information technology but also in gaining a more fundamental understanding of the mechanisms underlying gravity, could be enormous. Should Canada be bearing the brunt of the "cost" for these efforts? Will they pay off in the long run? The 21<sup>st</sup> century is the information age. Access to highly trained people will dictate how competitive a country will be in the long run. Foundational theoretical physics is one of the least resource intensive areas of exploration at the frontiers of knowledge. Thus, it provides an especially cost-effective way to stay at the forefront of one of the most cutting-edge fields of

science. In this sense, support for PI is a very efficient use of resources to foster a group of world class researchers in Canada and train Canadians in this information age.

### **Collaboration with Associated Institutions**

Through its formative years, PI has clearly been mindful of its impact on the surrounding Canadian research communities. The second of its three stated goals is to have a positive impact on the surrounding academic institutions. One strategy employed to attract faculty members during its start-up phase was the funding of associate faculty positions with the surrounding universities. This has been beneficial both to PI and its neighbors (Waterloo, Guelph, McMaster and Western) bringing seven top flight theoretical physicists who spend a minimum of one third of their time at PI, with the remainder at their host university. It is likely that without the core provided by PI, these associate faculty researchers would not have moved into the southwestern Ontario area. Clearly, this has been of great benefit to the universities hosting associates, allowing them to expand into other areas in physics—something that would never have happened in the absence of PI.

The nature of the associate member program is changing. Perimeter's proposal for further expansion foresees modest growth in the area of associate faculty members. The committee endorses using these positions as a tool to foster connections with complementary Canadian institutions and, more importantly, to attract and retain top level faculty when competing demands make it impossible for them to accept full time appointments in Waterloo. But this must not detract from PI's main goal of attracting full time resident faculty.

PI has also forged good working relationships with a number of complementary research institutions, including the Fields Institute for Mathematical Research in Toronto, the Institute for Quantum Computing on the Waterloo campus and the Canadian Institute for Theoretical Astrophysics (CITA, Toronto), by organizing joint workshops and sharing visitors to the southern Ontario area.

### **Collaboration with Canadian Research Community**

PI has made significant efforts to reach out to researchers from the related Canadian communities. They have made extensive use of their short-term visitor and affiliate programs to bring in colleagues for a few weeks, months or even for year-long sabbatical visits. As PI was starting up this clearly gave them access to the intellectual capital provided by the visitors. However it has also forged lasting collaborations with members of the Canadian and international theoretical physics community. Such bonds are clearly the lifeblood of any research institution as, in addition to fostering on-going research collaborations, it provides obvious sources for graduate students and postdoctoral researchers who may end up spending several years at the Institute.

In order to establish its position as a pre-eminent theoretical research institute, not only in Canada but in the world, PI has played a significant role in the

organization of conferences. These have ranged from the 1000-participant “Strings05” conference (jointly organized with the Fields Institute, the University of Toronto and the Pacific Institute for Theoretical Physics) to much smaller workshops (this fall they are hosting the eighth in a series of string-theory workshops that bring together a few dozen researchers from CITA, Toronto and Perimeter) hosted on-site at Perimeter. While these conferences and workshops have been an enormous success and have added to the growing reputation of the Institute, it is clear that there can be “too much of a good thing”. It appears that the resident researchers are managing this balance well; however the committee felt that some scaling back in this area would probably be appropriate and would not detract from either the main scientific mission or the secondary mission of providing links to the surrounding research community.

## **Concluding Remarks and Recommendations**

In a very short period of time, Perimeter Institute has grown from nothing to an important international center for theoretical physics. It has prominent research efforts in quantum information theory, foundations of quantum mechanics, quantum gravity and string theory. In these areas, they can compete for the best postdoctoral scholars and attract the highest quality visitors. PI is very visible on the international scene, having hosted some of the key international conferences. It has vibrant educational and outreach programs that have enriched the local community and are also of national and international scope.

PI has plans to expand over the next five years (almost doubling the number of faculty and postdoctoral appointments), greatly strengthening its groups in cosmology and particle physics. This will be difficult since these are highly competitive fields. However, PI succeeded in string theory despite the fact that this is also a field where the university system provides strong competition for the best faculty. Their expansion will be made a little easier by the fact that they now have an excellent reputation in theoretical physics.

The public-private partnership model used to fund the Institute since its establishment has proven extremely effective. The private funding has provided the special means and the flexibility that are the root of the success of PI; while the public funding has anchored the Institute to the public responsibility and the control mechanisms that reinforce its authority.

To be frank, the committee is amazed by the success that PI has had over the last few years. We congratulate them on a job well done. Given the great success of PI and the strong support it receives from the private sector, we recommend that Canada’s federal government continues to provide strong financial support to Perimeter Institute and be an active partner of this successful and promising enterprise.

# PI Objectives with Related Achievements

Provided to NSERC August, 2006

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## Summary of Objectives

In keeping with the Institute's twin mandates, the objectives of Perimeter Institute are to:

- 1. Establish PI as a premier international centre for foundational physics in accordance with our mission statement*
- 2. Integrate with the surrounding Canadian academic community and enhance the capability of and national reputation for fundamental physics research*
- 3. Develop and maintain a vigorous public outreach program geared to Canadians of all ages to promote the excitement of fundamental inquiry and scientific discovery*

# Objective 1

*Establish PI as a premier international centre for foundational physics in accordance with our mission statement*

“PI now has thriving groups of long-term researchers in both quantum gravity and quantum information theory; together with a strong and rotating group of postdocs, they now boast among the strongest - perhaps THE strongest - research groups in these subjects in the world.”

- SAC Report October 24-25, 2003

“It is a great honour to be here celebrating this extraordinarily ambitious scientific institute and I think all Canadians can be proud of this remarkably creative testament to human curiosity.”

- Margaret Geller,  
Smithsonian Astrophysical Observatory,  
PI Grand Opening, October 2004

“Perimeter Institute happens to be one of the world’s great hotbeds of quantum mechanics. They have one of the greatest departments and I try to come here as often as I can to learn from the folks at PI.”

- Seth Lloyd, MIT, April 2006

## Objective 1 Achievements

### a) Recruitment

64 Resident Researchers including:

- 10 Faculty
- 8 Associates
- 31 Postdoctoral Researchers
- 15 Long Term Visitors

### b) Research Groups

6 Groups Established in the Following Research Areas:

- Quantum Information Theory
- Quantum Foundations
- Quantum Gravity
- Superstring Theory
- Particle Physics
- Cosmology

Scientists work in an environment that fosters a diversity of approaches towards foundational issues in fulfillment of the Mission Statement.

### c) Scientific Advisory Committee

Past and present members include:

Ian Affleck (Emeritus), University of British Columbia	2001-2004
Artur Ekert, University of Cambridge	2001-2005
James Hartle, University of California at Santa Barbara	2001-2003
Chris Isham (Emeritus), Imperial College	2001-2005
Cecilia Jarlskog, CERN/Lund Institute of Technology	2001-2006
Sir Anthony Leggett, University of Illinois	2004-2007
Sir Roger Penrose, Oxford University	2001-2005
Joseph Polchinski (Emeritus), UCSB	2001-2004
Jorge Pullin, Louisiana State University	2003-2005
Paul Steinhardt, Princeton University	2003-2007
Scott Tremaine, Princeton University	2001-2006
Frank Wilczek, MIT	2003-2006

SAC Chairs have included Chris Isham, Scott Tremaine and Paul Steinhardt

### d) Publications and Citations

608 scientific publications in 49 different on-line and print journals, with a total of over 2700 citations to date.

### e) Prizes

Researchers continue to gather top honours, fellowships and awards including:

Rob Myers	2005 CAP/CRM Prize in Theoretical and Mathematical Physics
Daniel Gottesman	2003 MIT Technology Review's World's Top Young Innovators
Raymond Laflamme	Canada Research Chair in Quantum Information
Eric Poisson	2005 CAP Herzberg Medal for Outstanding Achievement by a Physicist ages 40 or less
Cliff Burgess	Killam Research Fellowship, Canada Council for the Arts

### f) Visitors

There have been a total of 643 short-term visits to PI by scientists from across Canada and around the world. Some notable researchers who took part in collaborations and provided seminars include:

- Michael Nielsen, University of Queensland (now becoming a PI Faculty member in 2007)
- Nima Arkani-Hamed, Harvard
- Alain Aspect, Centre National de la Recherche Scientifique
- Anton Zeilinger, University of Vienna
- John Preskill, California Institute of Technology
- Leonard Susskind, Stanford University

### g) Workshops & Conferences

29 high-level PI workshops and conferences (on and off-site) attracting 2452 participants over the past five years. Examples include:

- Emergence of Spacetime Workshop (2005)
- Quantum Information, Computation and Logic Workshop: Exploring New Connections (2005)
- Workshop on Quantum Gravity in the Americas: Status and Future Directions (2004)
- Workshop on Reference Frames and Superselection Rules in Quantum Information Theory (2004)

### h) Jointly Sponsored Conference & Workshops

11 joint-events serving 743 attendees have taken place in the new facility over the past two years. Examples of conferences and workshops that are aligned with or complement core research areas include:

- Mathematical Aspects of Quantum Adiabatic Approximation (PI, IQC, Fields Institute, 2006)
- Strings 2005 (PI, PITP, CIAR, IPP, PIMS, Fields, UofT, 2005)
- Cosmological Frontiers in Fundamental Physics (PI, APC, CIAR, 2005)

**i) Colloquia & Seminars**

703 total talks have been presented since inception – providing updates and new directions throughout the full spectrum of research areas. In addition, one in four talks provide content outside of, but related to, core disciplines.

**j) Opportunities for Postdoctoral Researchers**

Perimeter provides its many postdoctoral researchers as much research freedom and opportunity as possible to spur scientific activity and contributions. Opportunities include:

- Mentorship by senior Faculty members
- Organizing and hosting innovative conferences and workshops
- Organizing seminar series
- Ability to invite visitors on the level of Faculty
- Participation on scientific committees
- Supervision of Undergraduate Students
- Administrative assistance with, for example, grant applications
- Access to travel funds, office space and full research services.

“PI allows for a good combination of complete research freedom and contact with senior scientists. Having a summer student and participating in various committees was helpful in finding a Faculty job, since supervision/administration questions inevitably pop up during the interviews. I'm taking a Sr. Lecturer position at Macquarie U in Sydney. PI is probably the best place that I've been so far, both in terms of the research funding and support services, and its visitors and seminar programs.”

- Daniel Terno  
Postdoctoral Researcher  
Quantum Information Theory

**k) Establishment of Facilities**

After consultation with the research community and careful study of architectural designs that foster a wide variety of interactions and group activities, a two-stage infrastructure plan was initiated involving:

- 35 King Street North, Waterloo
  - This century old post office with clock tower was converted into a temporary home for the first PI resident scientists and visiting researchers. The 14,000 sq. ft. space, with offices and

collaboration areas, will continue to be used for additional research, seminars, workshops and outreach activities.

- 31 Caroline Street North, Waterloo
  - This 65,000 sq. ft. black-board lined research centre offers a mix of private and shared offices, collaboration areas, two seminar rooms, theatre and library. The award winning facility has been honoured with:
    - 2006 Governor General's Medal in Architecture;
    - 2005 Ontario Association of Architects Award;
    - 2005 Ordre des Architectes du Québec Award; and,
    - A citation in the 349<sup>th</sup> annual P/A awards.

Attention to information technology within the facilities supports researchers via webcasting of most lectures, teleconferencing and phone conferencing for collaborations as well as other state of the art A/V support.

## Objective 2

### *Integrate with the surrounding Canadian academic community and enhance the capability of and national reputation for fundamental physics research*

“Perimeter has been critical for me to come back to Canada. Its vision and its energy were so compelling that I could not miss the opportunity. Five years after having arrived in Waterloo, I can say that I am really proud of being part of this great endeavour.”

- Prof. Raymond Laflamme  
PI Associate Member  
CRC in Quantum Information, UW  
Director, IQC, UW; CIAR QIP program

“The joint hiring of Cliff Burgess by McMaster and Perimeter has brought enormous benefits to McMaster. Given the small size of the department and the heavy concentration in other areas, it would have been impossible for McMaster, on its own, to develop a high quality program in elementary particle theory.”

- Prof. John Berlinsky  
Chair of Physics and Astronomy  
McMaster University

“Perimeter Institute has already had a tremendous impact on theoretical physics in Canada. The first and main impact comes from the concentration of so many leading minds in one locale, which has already produced an amazing array of results. The second largest impact will perhaps be more profound in the long run: the establishing of Perimeter has raised the morale and energy levels of theoretical researchers all across the country, and the excitement is growing - we all have the feeling that this is the start of something truly grand. The capstroke, however, is Perimeter’s commitment to outreach and education at all levels. By making lasting connections to teachers, especially to the teachers of younger children, Perimeter has already seriously enriched the educational fabric of the country, and is helping to lay the groundwork for a scientifically and technically more literate populace, and a potentially more robust and much stronger economy.”

- Prof. Robert M. Corless  
Chair of Applied Mathematics  
University of Western Ontario

## Objective 2 Achievements

### a) Associate Program

This program has targeted and recruited eight current researchers in close conjunction with collaborating universities who also require expertise in similarly focused areas. Associate members currently include:

- Alex Buchel [2003] PhD Cornell (1999)  
University of Western Ontario  
Superstring Theory
- Cliff Burgess [2004] PhD University of Texas, Austin (1985)  
McMaster University  
Particle Theory
- Richard Cleve [2005] PhD University of Toronto (1989)  
University of Waterloo  
Quantum Information Theory
- Raymond Laflamme [2001] PhD Cambridge (1988)  
University of Waterloo  
Quantum Information Theory
- Michele Mosca [2001] PhD Oxford (1999)  
University of Waterloo  
Quantum Information Theory
- Ashwin Nayak [2003] PhD Berkeley (1999)  
University of Waterloo  
Quantum Information Theory
- Maxim Pospelov [2004] PhD Budker Institute (1994)  
University of Victoria  
Particle Physics
- Thomas Thiemann [2003] PhD RWTH Aachen (1993)  
Max Planck  
Quantum Gravity

### b) Affiliate Program

Affiliate membership provides 52 Faculty at Canadian universities with opportunity to be regularly involved with the Institute's wide variety of research activities.

**c) PI Faculty Involvement with Universities**

PI Faculty engage on campus via cross-appointment, adjunct status and by special invitation

**d) Off-site PI Co-Sponsored Conferences**

12 events attended by 1479 participants have been funded and/or supported by PI at other locations since inception.

Events include:

- Summer School on Strings, Gravity and Cosmology, held at UBC (2006)
- Workshop on N=1 Compactifications, held at Fields Institute (2005)
- Strings 2005, held at Fields Institute (2005)
- COSMO-04, held at University of Toronto (2004)
- Summer School on Quantum Information Science, held at University of Calgary (2003)

**e) On-site Joint Conferences**

11 joint conferences, summer schools and workshops of benefit to the Canadian physics establishment have been held on-site at the new PI facility within the past two years with total attendance of 743 participants. An event example includes:

- Theory CANADA 2 in cooperation with PITP, CITA, TRIUMF, U of A Theoretical Physics Institute, Winnipeg Institute for Theoretical Physics and the Canadian Association of Physicists (CAP)

**f) Courses Taught at Perimeter Institute by Institute Faculty**

The new PI facility is home to a growing number of courses taught by Faculty and Associate members which, over the past two years, have included:

- “Interpretation of Quantum Mechanics: Current Status and Future Directions” with Raymond Laflamme (2005);
- “Special Topics: Superstring Theory” with Rob Myers (2005); and
- “Introduction to Quantum Gravity” with Lee Smolin (2006).

**g) Opportunities for Graduate Students**

The Institute is dedicated to increasing the numbers and quality of physics graduate students in Canada and offers on-site participation with:

- Supervision by PI researchers
- Access to PI conferences, workshops, summer schools and seminars
- Office space with opportunity to collaborate in PI research activities
- Access to PI library and other research services

## **h) Opportunities for Undergraduate Students**

Students from partnering universities are encouraged to interact with PI by way of:

- Specific research projects under the supervision of a postdoctoral researcher
- Office space with computer, for one term, and opportunity to interact in additional research projects at PI
- Invitation to PI conferences, workshops, summer schools and seminars
- Access to PI library and other research services

## **i) Shuttle Service**

Transportation for resident scientists and visitors with surrounding institutes is made possible via the Institute's own shuttle services that, additionally, transports university students to the Institute for seminars, courses, colloquium and conferences. Destinations frequently include University of Western Ontario (London), McMaster University (Hamilton), University of Guelph, CITA and Fields Institute (Toronto), University of Waterloo and other select points and transportation links as required.

## **j) Links and Partnerships with Canadian Programs**

PI researchers are productively involved with a variety of Canadian organizations. Examples include the:

- Institute for Quantum Computing
- Canadian Institute for Advanced Research
- Canadian Institute for Theoretical Astrophysics
- Fields Institute
- Institute for Particle Physics
- Centre de Recherche Mathématique
- Pacific Institute for Mathematical Sciences
- Mathematics of Information Technology and Complex Systems research networks
- Shared Hierarchical Academic Research Computing Network

## **k) Memoranda of Understanding**

The Institute has signed agreements with 30 Canadian universities and institutions to serve as a focal point for all relevant members of the Canadian theoretical physics establishment. These include:

University of Alberta  
Augustana University  
Brandon University  
University of British Columbia  
Brock University  
University of Calgary  
Dalhousie University

University of Montreal  
University of New Brunswick  
Queen's University  
University of Regina  
Ryerson University  
University of Saskatchewan  
Simon Fraser University

University of Guelph  
Institute for Particle Physics  
Laurentian University  
University of Lethbridge  
McGill University  
McMaster University  
Mount Allison University  
University of Manitoba

University of Toronto  
University of Victoria  
University of Waterloo  
University of Western Ontario  
University of Windsor  
University of Winnipeg  
Wilfrid Laurier University  
York University

## Objective 3

*Develop and maintain a vigorous public outreach program geared to Canadians of all ages to promote the excitement of fundamental inquiry and scientific discovery*

“It is inspiring to see that this building is so beautiful and that it welcomes the public in the way that it does.”

- Frank Wilczek  
MIT

“EinsteinFest and the public lecture I attended in the winter remind me that well presented events serve two very important social services. As well as imparting facts and knowledge about science, outreach conducted by scientists also conveys to the audience the rigor, discipline and process of science.”

- Vic Tyrer  
Senior Policy Advisor  
Ontario Ministry of Research & Innovation

“It is with great pleasure that the Canadian Commission for UNESCO confirms its support and patronage for the International Summer School for Young Physicists. This initiative is an exemplary undertaking in the follow-up to the international year of physics and in the promotion of education and capacity-building in the basic sciences.”

- Dominique Potvin  
Natural Sciences, Programme Officer  
Canadian Commission for UNESCO

“I would like to thank PI once again for your teacher workshop initiative. It was well worth my first weeks' holiday, and I am sure it will positively affect not only my understanding and teaching of modern physics, but my teaching in general. I picked up many tips on effective teaching.”

- Myrnal Hawes, BC  
Einstein Plus participant

“My administrators were so impressed and so excited by what they saw and heard at the Institute. We are all looking forward to working with Perimeter to create opportunities for students to experience the wonders of physics!”

- Georgina Balascas  
Superintendent of Education  
Toronto District School Board

## Objective 3 Achievements

### a) Programs for Students

- Increased sessions of the “International Summer School for Young Physicists” (ISSYP) in Waterloo – now doubled in size and servicing 100 students each summer. Students attend from across Canada and around the world. Special links with UNESCO ensures participation by students from developing nations.
- “Physica Phantastica” in-class lectures on modern physics held coast to coast - including under serviced regions of Ontario
- Both programs have reached thousands of students with direct, face-to-face training, lectures from scientists and mentorship sessions.

### b) Programs for Teachers

- Increased sessions of the “Einstein Plus National Teachers’ Workshop on Modern Physics” providing educators from across Canada with in-depth presentations by scientists and opportunities to discuss pedagogical techniques. This program has more than doubled in size since inception.
- PI Workshops for educators held on location across Canada with emphasis on how to make concepts in modern physics more relevant, accessible and fun to learn
- Both programs have directly reached a total of over 1000 teachers

### c) Programs for the General Public

- Nearly 100 Public Lectures have taken place via a popular monthly lecture series and open house (46 lectures in total) as well as a festival series (38 lectures) and various special events held both on and off location. Many lectures attract 500 to 600 people per occasion and are, additionally, viewable to wider audiences on television and via the Institute’s website
- Monthly “Black Hole Sessions” provide drop-ins for coffee and Q&A with Perimeter Institute’s Director of Scientific Outreach and, frequently, a resident scientist or visitor.
- Special Events have included a PI Open House attracting 8000 in a single day and “EinsteinFest” attracting over 28,000 in three weeks for a comprehensive “World Year of Physics” celebration featuring hands-on experiments, exhibits, displays, thematic lectures and concerts in keeping with the 1905 era.

#### **d) Researcher Participation in Outreach**

Programming benefits directly from the wisdom and participation of scientists. The Director of Scientific Outreach, himself a PhD in Quantum Information Theory, deliberately utilizes research staff to:

- Vet and improve upon new, educational content
- Provide key-note presentations and mentorship sessions within ISSYP and Einstein Plus to the benefit of students and teachers
- Meet with members of the general public via monthly “Black Holes”, festivals and special events

#### **e) Partnerships and Other Involvement**

The Institute interacts with a variety of regional, national and international science education organizations. Participation occurs in many forms and includes:

- Events held on location at PI, such as the Ontario Association of Physics Teachers (OAPT) annual conference
- Off-site conference participation, including the American Association of Physics Teachers (AAPT) gathering
- Partnership with UNESCO, mentioned above, to better target and attract students from developing nations for ISSYP
- Deployment of PI outreach content in coordination with the national “PromoScience” program and with the provincial “Youth Science and Technology Outreach Program” (YSTOP)
- Engagement with the Toronto District School Board (TDSB), Canada’s largest school board via on location programming involving the various student, teacher and general public presentations
- Co-sponsorship of students via science fairs, the Canadian National Physics and Chemistry Olympiad as well as in-kind support to related groups
- Partnership with the Canadian Association of Physicists (CAP) in presenting a 19-stop, cross-country lecture tour in both of Canada’s official languages

#### **f) Event Horizons**

Perimeter Institute also shares the award winning facility with the wider community through Event Horizons – a series of ticketed and sponsored events involving musical concerts, art talks and cultural events.

#### **g) Media Availability**

Fascination with global developments in science and education are occasionally reported upon by media and, from time to time, the Institute is pleased to provide comment as part of its outreach efforts and raise awareness of Canada’s role in basic research.