

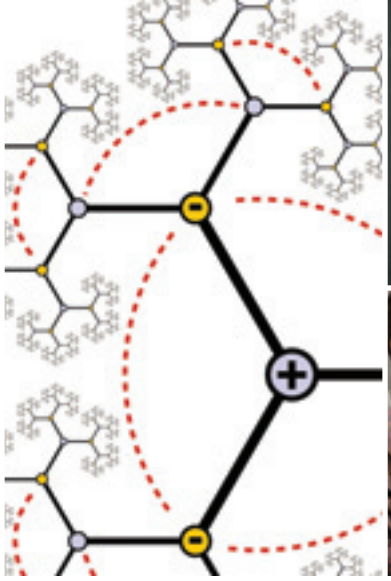

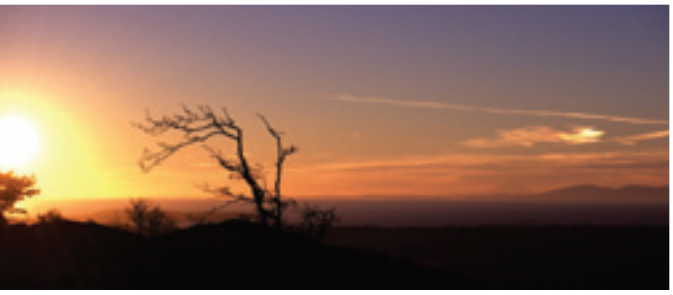

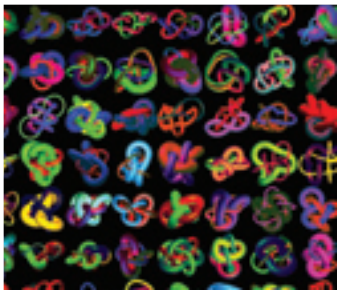

Solutions
for a Complex Age

Long Range Plan for Mathematical and Statistical Sciences Research in Canada 2013–2018

2013–2018 | Report of NSERC's Long Range Plan Steering Committee for the Mathematical and Statistical Sciences

Acknowledgements: The Long Range Plan Steering Committee for the Mathematical and Statistical Sciences is pleased to present our Long Range Plan for 2013–2018 and beyond. This plan—the first for our disciplines—was prepared at the request of the Natural Sciences and Engineering Research Council (NSERC). Details about the Steering Committee, its terms of reference and consultations with our research communities are provided in Appendix A. NSERC funding for the preparation of the plan is gratefully acknowledged.

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For photo information please see inside back cover.

Solutions
for a Complex Age

Long Range Plan for Mathematical and Statistical Sciences Research in Canada 2013–2018

Executive Summary

The mathematical and statistical sciences are essential to discovery and innovation in Canada and throughout the world. A key source of transformative breakthroughs in science, they provide both new ideas and fundamental tools for scientific and technological innovation.

Advances in mathematics and statistics are vital to the growth and smooth functioning of the Canadian economy, and to our society as a whole. As the 21st century progresses, they will play a crucial role in helping to understand and solve many of the energy, environmental and health challenges that are priorities for Canadians.

Mathematics and statistics are everywhere—from the way we manage our investments to the way we track our transportation systems or explore the outer reaches of space. The theories, models and methods of the mathematical and statistical sciences are part of an almost invisible foundation that supports the way we interact with one another, transact our business and construct the world around us.

Mathematics and Statistics—Advancing Discovery and Innovation

Canada aims to be a top global performer of science, technology and innovation in order to thrive in a global knowledge economy and to maintain the quality of life that Canadians cherish. A strong capacity in mathematics and statistics research and training in Canada is central to achieving this goal.

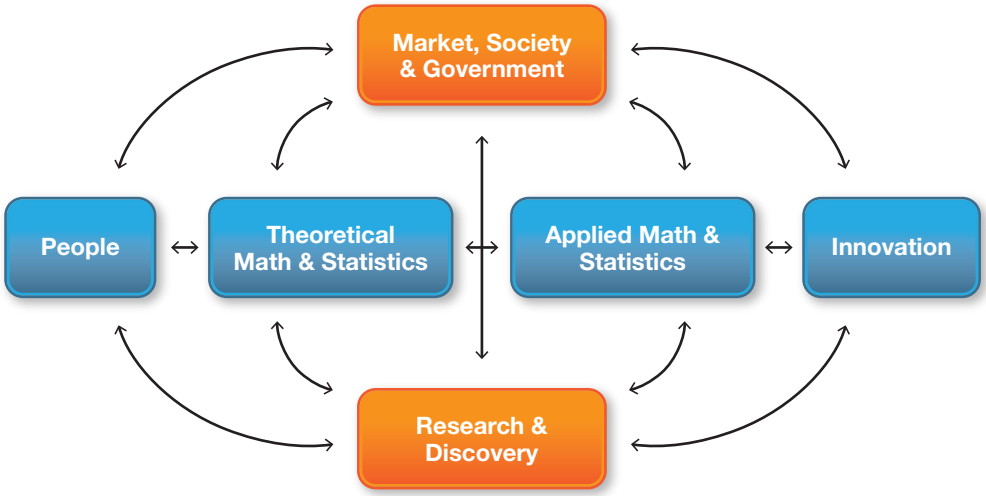
The Power to Transform Science and Technology

The mathematical and statistical sciences are fundamental to the advancement of science. Researchers across the physical, health and social sciences depend on ideas from mathematics and statistics to explore new concepts, analyze their data and verify their findings.

The mathematical and statistical sciences—both pure and applied—can be found at the heart of almost every effort to push the boundaries of science and related innovation, powered by technological advances and the ubiquity of data. Mathematical and statistical methods enable us to model complex ecological systems, assess new materials and crack the codes of nature. They also drive advances in computer science, with application to most scientific and technological advancements.

There is no "best before" date on a theorem in mathematics, and the deep and beautiful foundations of the subject have inspired thinkers for many centuries. Mathematics has also shown, time and again, an uncanny ability to cross boundaries between the sciences and to drive forward great leaps in scientific understanding and countless technological applications. This power to transform

Accelerating Innovation and Discovery—Engaging Mathematics and Statistics



Collaborations with research teams from across science, industry and government enable mathematicians and statisticians to explore themes linked to real-world problems and to use the ideas needed for these collaborations as inspiration for their own research. Strategic feedback of this kind is advancing the mathematical and statistical sciences at an unprecedented rate and contributing to S&T solutions for important global challenges and Canadian priorities.

has been particularly notable in physics, where mathematics has laid the groundwork for revolutionary breakthroughs in areas as diverse as quantum mechanics and string theory.

The impact of statistical science can also be observed across almost all fields of intellectual enquiry. The force of the oncoming "data tsunami"—as information and communications technologies enable business, governments and individuals to collect and manipulate ever-increasing amounts of data from diverse sources—will only accentuate the demand for statistical expertise.

Accelerating Discovery and Innovation in the 21st Century

Many see the 21st century as a Golden Age for the mathematical and statistical sciences around the globe. Already, the first decade has brought an unprecedented level of research activity in both mathematics and statistics, generating important theoretical breakthroughs and spinning off new areas for exploration and surprising possibilities for application.

Both sciences are bursting with new ideas as the borders between mathematical and statistical sub-disciplines fall away and many of the world's most talented people are attracted to study or practice mathematics and statistics. Add to this the ever-evolving range of high-power computational and graphical tools now available to the research community, and breakthroughs in almost any area of the mathematical and statistical sciences—and related discovery and innovation—are possible.

In a world increasingly characterized by complexity, the ability to tease apart difficult problems and work with multifaceted systems is essential. Mathematical and statistical scientists have the expertise and the advanced theoretical and computational tools available to help generate game-changing technologies and ideas that can drive the global economy, and to implement innovative solutions to many of the world's most pressing problems.

Changing Relationships—Mathematics and Statistics as a Strategic Investment

Researchers with mathematical and statistical expertise are increasingly sought after to contribute to projects of all kinds across the sciences, government and industry. This collaboration has unleashed a wave of creative thinking and new experimental approaches that have had an extraordinary impact on discovery and innovation in all areas. The influence on mathematics and statistics has been similarly profound—the testing of mathematical and statistical theory in the real world has raised new and interesting questions for mathematicians and statisticians to pursue and solve.

As the link between scientific discovery and innovation tightens—and the global research enterprise becomes more interdisciplinary and fast-paced—the strategic importance of the mathematical and statistical sciences only grows. The ability to explore theories and to model situations using mathematical insights and statistical methods is becoming ever more essential to science and engineering, reducing risk and cost by enabling faster, more responsive feedback loops between theory, discovery and application.

The value generated by investments in the mathematical and statistical sciences is exceptionally high. Both sciences are relatively low-cost in terms of their capital infrastructure requirements, yet their influence on talent, discovery and innovation—the three key building blocks of a knowledge-based society and economy—is both broad and deep.

Our Vision

Canada will be a world leader in the mathematical and statistical sciences, and a driving force in interdisciplinary research and innovation that contributes solutions to important Canadian and global challenges.

Vision for Canadian Mathematics and Statistics

Canada is well placed to make important contributions to the evolution of the mathematical and statistical sciences at the international level—both by pushing the boundaries of pure mathematics and theoretical statistics, and by excelling in linking these ideas to the grand challenges that will define human progress in the 21st century. Our communities of researchers have the vision, talent and expertise to achieve international excellence and, in particular, to be at the leading edge of interdisciplinary research and innovation. The Council of Canadian Academies (CCA) report, *The State of Science and Technology in Canada, 2012* (Council of Canadian Academies, 2012), shows Canadian mathematics and statistics as having improved in both relative citation rates and numbers of publications since 2006. Our mathematical and statistical sciences research base is ranked 9th in the world by Average Relative Citation rates, and 5th in the world in a survey of top-cited international researchers.

Notably, our research communities are already at the forefront of integrating mathematical and statistical expertise into interdisciplinary teams. Mprime (formerly Mitacs[1]) and other collaborative initiatives have built a strong capacity for interdisciplinary work with industry and other sectors of society.

The CCA's 2012 report on the state of S&T noted the high rate of international collaboration among Canadian researchers in the mathematical and statistical sciences. Using new bibliometric indicators designed to reflect the increasing interdisciplinarity of research, it also pointed to some of the hot spots where interdisciplinary research is most intense. From the report: "Canada's most rapidly growing research clusters are associated with networking and wireless technologies, information processing and computation, advanced data analysis, digital media technologies, speech and image recognition, carbon nanotubes and graphene, fuel cell technology, and space and planetary science." Canada's mathematics and statistics research communities are actively engaged with discovery and innovation in many of these areas. Indeed, Mprime has supported projects in six of the eight emerging research clusters mentioned above.

1 Prior to May 16, 2011, the Network of Centres of Excellence (NCE) in the mathematical sciences was known as MITACS Inc. Effective May 16, 2011, the mathematical sciences NCE assumed the name Mprime Network (Mprime Network © 2011). In this document, we use Mprime for convenience to refer to the NCE both before and after the restructuring in 2011.

Our goal for our research communities over the next five to ten years is to build on this expertise to bring the mathematical and statistical sciences to the fore in finding solutions to issues that really matter to Canadians and to the world—from energy to security to environment to health care.

Achieving Our Vision—Three Fundamentals

Our vision for building this capacity rests on three fundamental pillars:

- **People** Ensuring Canada's researchers are among the best in the world, and that Canada has the highly qualified personnel available to meet the demand for the mathematical and statistical sciences in a knowledge economy and complex society.
- **Research and discovery** Maintaining a vibrant, world-class, basic and applied research base that can drive discovery and innovation.
- **Innovation and connections** Fostering innovative approaches that advance interdisciplinary research, embed researchers in industry, and facilitate the flow of ideas between researchers and their potential partners across science, industry and government.

Realizing this vision—and its many potential benefits for Canadians—will require a strong commitment to continued investment in mathematical and statistical sciences research, and a willingness to find new ways to collaborate with Canada's research community and its funders.

For Canada to have the mathematics and statistics capacity it needs to advance discovery and innovation over the coming decade, all three of these fundamental pillars must be robust and be well connected to each other.

This Long Range Plan describes the opportunity and challenges that cut across all three of these pillars, and makes interrelated recommendations aimed at strengthening all three.

What We Heard—Community Concerns and New Initiatives

Canada's researchers in the mathematical and statistical sciences have the expertise, drive and momentum to bring real innovation to the most challenging and complex problems of importance to Canada and the world. However—despite these considerable strengths—there are challenges that may limit our ability to move this vision forward. Some of these are being actively addressed at the community level with the launch of new initiatives. Others will need to be addressed in collaboration with the Natural Sciences and Engineering Research Council (NSERC), the primary source for funding of mathematical and statistical sciences research in Canada.

Maintaining the pipeline Demand for skilled researchers and instructors is outstripping supply in our universities, as our faculty attempt to provide training in the mathematical and statistical sciences for the next generation of scientists, engineers and business professionals. Enrolment at the graduate level in both the mathematical and statistical sciences has more than doubled over the past decade. Discovery Grants are an essential resource for funding the pipeline for highly qualified personnel: researchers use most of their grant funding to support students at the undergraduate, post-graduate and post-doctoral levels. A well-resourced system for research and training is essential if Canada is to have ready access to the talent, knowledge and innovation we will most certainly need to sustain a strong economy in the years to come.

Levels of investment Canada has forged a record of high achievement in the mathematical and statistical sciences with comparatively modest investment in international terms. The research community has been resourceful in leveraging the basic support it receives from the federal government with funding from other sources, including the private sector and international funding agencies. Nevertheless, current gains and future advances will be in jeopardy without further and continued investment in Canada's mathematical and statistical sciences research capacity.

Flexibility and diversity Maintaining breadth, depth and diversity is essential to the health of mathematical and statistical research. This means maintaining capacity to support research and training at the individual researcher levels at both large and small institutions. It means encouraging and building diversity across geography, gender and culture. It means actively supporting programs of basic research, not only to meet future needs for innovation in the mathematical and statistical sciences, and the sciences that rely on their findings and advances, but for their important contributions to knowledge. And it means actively supporting interdisciplinary research, thematic and collaborative resources, and partnerships and innovation.

Interdisciplinary research Research in the mathematical and statistical sciences is often inherently interdisciplinary in nature, and many exciting research advances are occurring in collaboration with other disciplines, and in the creation of new

hybrid disciplines. This is especially true in applied mathematics and in statistics, although researchers in pure mathematics also find themselves involved in such collaborations. Our communities expressed concern that interdisciplinary research proposals can be difficult to evaluate, and may fall between the cracks of two or more Evaluation Groups at NSERC, or between the cracks of the three granting councils. The problem is particularly acute in biostatistics, but affects other areas of research as well.

Thematic and collaborative resources Canada is home to three international mathematical sciences institutes: the Centre de recherches mathématiques, the Fields Institute for Research in Mathematical Sciences and the Pacific Institute for the Mathematical Sciences. Canada also hosts the Banff International Research Station, a unique and inspiring international collaboration with the US and Mexico. A new Canadian Statistical Sciences Institute is in development.

Research institutes are established assets for the mathematical and statistical sciences research communities around the world. Canada has been an important contributor to this trend: international experts rated Canada's infrastructure for the mathematical and statistical sciences very highly in *The State of Science and Technology in Canada* report (Council of Canadian Academies, 2012). The Long Range Plan endorses close cooperation among the institutes through the development of a Canadian Network of Mathematical and Statistical Sciences Institutes. The Long Range Plan also recommends investment in these resources by ensuring that funding for the institutes and for the Banff International Research Station is preserved under the envelope model for funding mathematics and statistics.

Together—and individually—these thematic and collaborative resources are key supports for our communities' vision: for Canada to be a world leader in the mathematical and statistical sciences, and to be a driving force in interdisciplinary research and innovation that contributes solutions to important Canadian and global challenges.

Partnerships and innovation The mathematical sciences community created a vibrant and uniquely successful Network of Centres of Excellence for the Mathematics and Information Technology of Complex Systems, since renamed Mprime. The participation of Mprime in the Network of Centres of Excellence program ended, under the rules of that program, on March 31, 2012. The loss of this federal funding, about $5.4M per year, will impact hundreds of companies, professors and students who all came together under the Mprime umbrella to address some of the most pressing challenges the country faces. The loss also jeopardizes hundreds of linkages between Canada's industrial base and the mathematical and statistical sciences research communities.

The mathematical and statistical sciences are assuming new and important roles in Canada's innovation agenda. Research in mathematics and statistics provides a conceptual framework and a quantitative language for describing and measuring phenomena, and students trained in the mathematical and statistical sciences bring problem-solving skills to bear on pressing industrial problems.

The Long Range Plan envisions a future role for Mprime as an over-arching national network, serving to bring together mathematical and statistical scientists from businesses, universities, research centres, and financial and technology organizations to stimulate innovation. Mprime will serve as a resource for both industry and academia in providing a platform for developing research proposals to NSERC's Research Partnerships Program.

Key Directions and Recommendations

This Long Range Plan is the first of its kind for the mathematical and statistical sciences research community in Canada. It is the product of more than a year of consultation and discussion within our communities. It is also informed by the Government of Canada's Science and Technology strategy: *Mobilizing Science and Technology to Canada's Advantage.*

The Long Range Plan Steering Committee has identified the following key directions and areas for investment in the Canadian mathematical and statistical sciences. Individual chapters of the report outline community initiatives aimed to advance the mathematical and statistical sciences in Canada over the next five to ten years, and give more detailed recommendations from the Steering Committee. A complete list of all the recommendations can be found in Chapter 8 of the report.

We recommend that NSERC:

- Invest in Canada's mathematical and statistical sciences research via Discovery Grant levels that reflect the importance of the research base to Canada, and that acknowledge that the costs of research are similar to those in several related science and engineering disciplines.
- Invest in Canada's network of thematic and collaborative resources in the mathematical and statistical sciences, including the newly developing Canadian Statistical Sciences Institute, and ensure that the funding envelope has a boundary between Discovery Grant funding and funding for these resources, to enable both to flourish and support each other.
- Augment the funding envelope to include the Research Partnerships Portfolio, enabling the mathematical and statistical research communities—working through the institutes and through Mprime—to provide a platform for a wide range of successful partnerships between the mathematical and statistical sciences and industrial partners.
- Establish a committee of leading mathematical and statistical scientists, chosen in consultation with the research communities, to oversee the implementation of this Long Range Plan, represent the research communities to NSERC, and develop research linkages among the mathematical and statistical sciences and allied science disciplines.

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CHAPTER 1

Solutions for a Complex Age

Canada aims to be a top global performer of science, technology and innovation in order to thrive in a global knowledge economy and to maintain the quality of life that Canadians cherish. International excellence in science and engineering—both in terms of groundbreaking research and the effective commercialization of innovation—are essential to our nation's ability to achieve sustainable economic growth, effective environmental stewardship and an advanced society. The mathematical and statistical sciences are fundamental to scientific discovery and technological innovation—a strong capacity in mathematics and statistics research and training is central to achieving this goal.

Math and Stats are Everywhere

Mathematics and statistics are everywhere—their methods, ideas and equations underpin almost every process used to advance science, and many activities in business, industry and society.

It is mathematics and statistics that help us map the brain or image tumours, move products to market, or search the Internet. It is mathematics that helps us navigate the seas, the airways or space travel. It is statistics that helps us analyze opinion polls and ensure fair elections. And it is mathematics and statistics that help us invest in the markets, calculate our pensions and predict the weather.

The basic use of mathematics is as old as the concept of the marketplace and humanity's desire to exchange and to store goods, construct buildings or manage social interactions. However, the advent of the digital age has made the use of mathematics and statistics almost ubiquitous, and that much more essential—both in science and in the everyday world. Mathematical and statistical theory, equations and algorithms are fundamental to the countless computational tasks and the information and communications technologies we have so rapidly come to rely on. They are also vital to protecting and ensuring the smooth functioning of the digital universe. Whether our goal is to predict market preferences, to engineer sustainable buildings or to explore the frontiers of space, pure mathematics, applied mathematics and statistics all play important roles.

Advancing Discovery and Innovation

The mathematical and statistical sciences are essential to discovery and innovation in Canada and throughout the world. A key source of transformative breakthroughs in science, they provide both new ideas and fundamental tools for scientific and technological innovation. Advances in mathematics and statistics are vital to the growth and smooth functioning of the economy, and to society as a whole. As the 21st century progresses, they will play a crucial role in helping to understand and solve many of the energy, environmental and health challenges that are priorities for Canadians.

The book of nature "is written in the language of mathematics."

Galileo, *The Assayer* (1623)

Math's Advantage

Mathematics is known for its **universality**—that is, for its ability to cross over scientific boundaries and to bring insight to virtually every discipline in science and technology. Mathematics has been called the "fabric" of science and technology —you cannot always see it, but it is there, underpinning almost every advance. The storehouse of ideas from theoretical mathematics can be explored endlessly to bring new insights or tools to almost every branch of the natural, physical or social sciences. It is equally versatile in stimulating and supporting innovation in industry, government and civil society.

The Power to Transform Science and Technology

The formal study of mathematics dates back to ancient Greece, making it one of the oldest of the sciences. For more than 2000 years, mathematicians have probed the intricacy of the world of numbers, both for its own abstract beauty and to expand human understanding of the universe in which we live.

Mathematical theories—pure and applied—are a product and reflection of the human mind. Yet, mysteriously they often reveal the basic organizing principles at work in the biological and material world around us—principles that have eluded understanding through direct observation alone.

It is this desire to understand and predict the physical world that underpins what Nobel prize-winning physicist and mathematician Eugene Wigner called "the unreasonable effectiveness of mathematics" as the foundation of the natural sciences. In his famous essay by the same name, Wigner commented that, "the mathematical formulation of the physicist's often crude experience leads in an uncanny number of cases to an amazingly accurate description of a large class of phenomena" (Wigner, 1960).

Time and time again, mathematics has shown an incredible ability to cross the boundaries between the sciences and to drive forward great leaps in scientific understanding and countless technological applications. This power to transform has been particularly notable in physics, where mathematics has laid the groundwork for revolutionary breakthroughs in areas as diverse as quantum mechanics and string theory.

Statistical science is equally foundational. It is a younger discipline—the first accurate theories of probability were not developed until the 17th century, and the modern theory of statistics dates from the early 20th century. However, its impact has been felt across almost all fields of intellectual enquiry, from particle physics to literary history. Today, the increasing importance of statistical science to research of all kinds, together with the increasing attention to "quantitative literacy," has created enormous demand for statistical expertise across science, government and industry.

Many statisticians and applied mathematicians find their research inspiration in direct collaborations with scientists from other disciplines. The scientific questions explored through these collaborations frequently lead to the development of new statistical and mathematical models and methods, which in turn can be applied to problems in completely different scientific fields.

With the world of science and industry now on hyperdrive, the foundational role of the mathematical and statistical sciences is especially apparent. The mathematical and statistical sciences—in their pure and applied forms—can be found at the centre of almost every effort to push the boundaries of science and related innovation, powered by technological advances and the ubiquity of data.

Mathematical and statistical models of disease processes lead to breakthroughs in treatment, and in public health. Mathematical and statistical methods enable us to model genomes, assess new treatments and crack the codes of nature. And mathematics and statistics drive advances in computer science, with application to most scientific and technological advancements. Google's page rank system, for example, builds on the mathematics of graph theory and linear algebra, and the statistical analysis of pattern matching.

Changing Relationships—Pushing the Frontiers of Science and Innovation

The relationship between statistics and applied mathematics, and with their fields of application, is highly dynamic and interconnected—and has always been so. However, the reciprocal character of this relationship has greatly intensified over the last decade. Researchers with mathematical and statistical expertise are increasingly sought after to contribute to projects of all kinds across the sciences, government and industry. This collaboration has unleashed a wave of creative thinking and new experimental approaches that have had an extraordinary impact on discovery and innovation in all areas. The influence on mathematics and statistics has been similarly profound—the testing of mathematical and statistical theory in the real world has raised new and interesting questions for mathematicians and statisticians to pursue and solve.

Statistics—Helping Us to Interpret the World of Data

While Al-Kindi, the "Philosopher of the Arabs" used statistical analysis for code breaking in the 9th century, the modern theory of statistics was laid out by Sir Ronald A. Fisher in the 1920s. Fisher spent most of his career at the Rothamsted Agricultural Station, where he pioneered the use of experimental design, authored the hugely influential *Statistical Methods for Research Workers,* and developed nearly all the modern concepts for statistical inference. He also established the field of population genetics; indeed he was nominated by Richard Dawkins as the "greatest biologist since Darwin" (Dawkins, 2010). The fields of statistics and population genetics continue to be closely linked.

From Geometry to Black Holes—How Math Transforms Physics

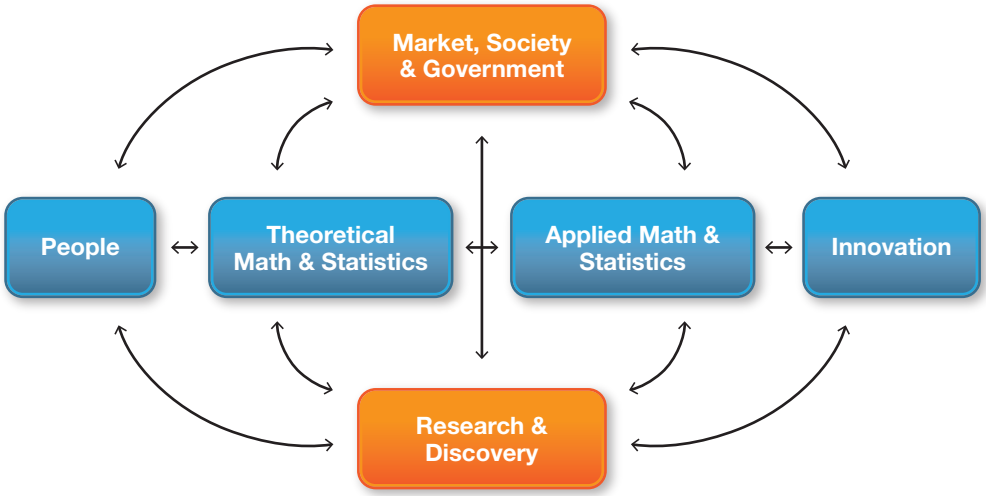
When Albert Einstein was puzzling over his theory of relativity in the early 20th century, he found the clues he needed in the correspondence written by Bernhard Riemann, a German mathematician who had worked some 60 years earlier in the field of geometry.

Riemannian geometry provides a precise way of describing and computing the geometry of surfaces in higher dimensions (those considered to have more than three dimensions) and the behaviour of curves upon them. First developed by Riemann around 1850, this set of theories has had a major influence on many fields of mathematical science, including group theory, algebra and differential topology.

Picking up on Riemann's thinking, Einstein's theory describes how gravitation is woven into the fabric of space-time through curvature and its effect on geodesic lines. In turn, the mathematical analysis of Einstein's field equations later led to the prediction of the existence of amazing objects such as black holes and to various big bang scenarios for the cosmological models of the universe.

The entire formulation and analysis of this set of theories in physics uses the mathematical structures discovered by Riemann.

Accelerating Innovation and Discovery—Engaging Mathematics and Statistics



Collaborations with research teams from across science, industry and government enable mathematicians and statisticians to explore themes linked to real-world problems and to use the ideas needed for these collaborations as inspiration for their own research. Strategic feedback of this kind is advancing the mathematical and statistical sciences at an unprecedented rate and contributing to S&T solutions for important global challenges and Canadian priorities.

The Unplanned Impact of Mathematics

A recent article in *Nature* entitled "The Unplanned Impact of Mathematics" underscores the unexpected—yet frequent—influence of mathematical research on everyday life and commerce. "Trying to solve real-world problems, researchers often discover that the tools they need were developed years, decades or even centuries earlier by mathematicians with no prospect of, or care for, applicability." From modems to computer games and insurance, the article highlights how many of the technologies we take for granted are founded on mathematics that was developed for its own interest and beauty (Rowlett, 2011).

The influence of this trend can be felt across all of the sciences—accelerating the pace and impact of discovery and innovation in many areas of importance to science and humanity. Many mathematicians and statisticians continue to explore themes at the theoretical level for their intrinsic value, and beauty. But more and more, researchers from other disciplines see mathematics and statistics as an incredible treasure chest of new approaches that can open the doors to discovery in unexpected ways.

Indeed, as the link between scientific discovery and innovation tightens—and the global research enterprise becomes more interdisciplinary and fast-paced—the strategic importance of the mathematical and statistical sciences only grows. The ability to explore theories and to model situations using mathematical insights and statistical methods is becoming ever more essential to science and engineering—reducing risk and cost by enabling faster, more responsive feedback loops between theory, discovery and application.

An immediate example is the application of mathematical and statistical modeling to health research. Advanced imaging and computer-based modeling are revolutionizing our understanding of the human brain and opening doors to everything from high-precision techniques for brain surgery to new treatments for neurological disorders such as Parkinson's disease. These new digital technologies are highly dependent on applied mathematics to tailor the software needed to gather the right patient data or images for a particular medical application. From a research perspective, these techniques enable investigators to narrow their field of inquiry more quickly, with the potential to reduce research costs and reduce risk to patients.

Table 1.1 Math Making a Difference
The mathematics behind everyday and not-so-everyday things

Algebra and Number Theory	CDs and DVDs, cryptography and secure communications (cell phones and banking), Google's Page Rank® system, 3D modeling and animation software
Geometry and Topology	Robotics, GPS systems, sensor networks, space mission design
Real and Complex Analysis	Aircraft design, wireless, radio and TV (electromagnetic spectrum), MRIs, spectroscopy
Partial Differential Equations	Waves, systems modeling (wound healing, tumour growth and tsunami prediction), radar imaging, MRIs and CT scans, finance
Combinatorics	Quantum theory, Internet server connections, scheduling, analysis of networks
Numerical Analysis	MRIs, imaging and compressed sensing, signal processing
Functional Analysis and Operator Algebras	Quantum information theory, modeling and design, machine learning
Spectral Theory	Spectroscopy
Optimization and Control	Electromechanical systems (cars, aircraft, power grids), logistics, feasibility studies

Derived from *Math Overflow* (Math Overflow, 2010)

Another example of the importance of mathematics and statistics as strategic research tools is the rapidly developing field of statistical machine learning. Statisticians, applied mathematicians and computer scientists are addressing the challenges of the oncoming data tsunami generated by information and communication technologies, the information commons and a growing global population. Advances in data mining and information management will be essential just to keep abreast of this tide of information, let alone to reap its advantages for science, society and commerce. Canada and the world's ability to respond to this challenge will require continued innovation and advances in statistics, mathematics and computer science. Again, this very innovation will open new doors to further advances in the statistical, mathematical and computing sciences.

Table 1.2 Stats Making A Difference
Probability and statistics—Finding patterns amidst the noise

Probability and Stochastics	Biology, medicine, finance, stock markets, economics, epidemic spread, fluid flow
Biostatistics	Drug development, population genetics, nutrition, environmental health, population health, assessment of medical treatments, clinical trials
Networks and Graphs	Psychology, education, sociology, causality
Extreme Value Theory	Finance, climate, hydrology, insurance
Spatial and Space-Time Models and Methods	Weather prediction, data compression, ergonomics, cartography, geology, machine learning
Functional Data	Fluid dynamics, growth curves, climate change, biomechanics, geophysics
Data Mining and Machine Learning	Astronomy, pharmacokinetics, bioinformatics, robotics, artificial intelligence, high-energy physics
Surveys and Sampling	Animal abundance studies, consumer behaviour, political opinion polls, population health
Actuarial Science	Pensions, health policy, risk, insurance, demography

Canada's Rising Stars

Over the last decade, Canadian researchers have received a bevy of international awards—reflecting Canada's international stature in mathematics and statistics.

Statistics
Between 1992 and 2012, three winners of the Committee of Presidents of Statistical Societies (COPSS) Presidents' Award were Canadian and working in Canada. The Presidents' Award is the most prestigious international award for statisticians under 40. Two resident Canadians have given the Fisher Lecture at the Joint Statistical Meetings—the highest award for senior researchers in statistics.

Mathematics
International honours for Canadian mathematicians include 15 Sloan Fellows in the past 10 years, and a remarkable seven speakers at the 2010 International Congress of Mathematicians (ICM). The Congress is held every four years, and an invitation to speak at the ICM is a significant mark of distinction.

Canada Research Chairs
Canada's Canada Research Chairs (CRC) program highlights the achievements of Canada's top research talent and helps attract some of the best researchers to Canada from around the globe. Canada's universities have 48 CRCs in mathematics and 11 CRCs in statistics and probability.

The Next Generation
Canada's high school competitors in the 2012 International Mathematics Olympiad turned in a 5th-place performance, their best ever. Over 150 countries compete annually in this "Intellectual Olympics." Our six-member team has brought home 29 individual medals in the past five years.

Math and Stats—Generating Outstanding Returns

The value generated by investments in the mathematical and statistical sciences is exceptionally high. Both sciences are relatively low-cost in terms of their capital infrastructure requirements, yet their influence on *talent, discovery and innovation*—the three key building blocks of a knowledge-based society and economy—is broad and diverse.

People The mathematical and statistical sciences are vital to the development of highly skilled personnel throughout the sciences and the economy. Both sciences foster abstract thinking and empower people to apply creativity to advantage. Graduates with strong training in mathematics and statistics can be found using their critical thinking and analytical skills in industry, government and academia. They are making a difference across sectors as diverse as physics, biology, information and communications technologies, aerospace, finance, manufacturing, agriculture, oil and gas, mining, forestry, ecosystem management, population health, and medical diagnostics and treatments.

Mathematics also frequently acts as a portal to science, technology, engineering and mathematics (STEM) careers. Often students' first exposure to STEM comes from the study of mathematics in their early school years. The mathematical and statistical research communities in Canada are very active in public and educational outreach. While this Long Range Plan (LRP) addresses research and research training, it is important to stress that improved mathematics and statistics training right from early childhood is vital to Canada's future in a technological world.

Research and discovery The power of the mathematical and statistical sciences lies in part in their ability to supply a common structure and language to science and technology. Mathematical formulas and statistical methods allow people to speak the same quantitative language and to apply shared principles to the questions they are exploring. They are fundamental to the scientific method, facilitating interdisciplinary collaboration and the translation of discovery into innovation.

At the same time, the lifespan of a mathematical theory is exceptionally long. Unlike other sciences where discoveries and theories are often quickly overtaken by the next discovery, there is no "best before date" on a mathematical proof. As noted earlier with the link between Riemannian geometry and Einstein's theory of relativity, the value of a theory may not be immediately apparent. However, theories from pure mathematics continue to surprise over the years through application to contemporary mathematical, scientific and engineering dilemmas. The result is often breakthroughs in scientific understanding, new technologies and products, or other practical uses. This represents tremendous value to both science and to society as a whole.

Innovation and connections The pervasive use of mathematics and statistics across the sciences and their application in finance, industry and government

magnifies the impact of basic research results that flow from these two fundamental sciences. The interplay between mathematics, statistics and the other sciences—plus the flow of ideas from theory to applied mathematics and statistics—has a strong impact on innovation, wealth creation and the quality of life of Canadians and people around the globe.

Pursuing International Excellence—Canada's Mathematical and Statistical Sciences Research Communities

The good news for Canada is that our research community excels at the mathematical and statistical sciences. As a Group V member of the International Mathematical Union (IMU), Canada's contributions to international mathematics and statistics are considered to be of the highest calibre, with our research communities ranked among the world's leading performers in both sciences.

The Council of Canadian Academies' recent report—*The State of Science and Technology in Canada, 2012*—shows that Canadian mathematics and statistics have improved in both relative citation rates and number of publications since 2006, and ranks Canadian mathematics and statistics 9th in the world by Average Relative Citation rates. It goes on to say that, "Canada is well regarded internationally in Mathematics and Statistics, being ranked 5th in the world by top-cited international researchers" (Council of Canadian Academies, 2012).

Canada's communities have achieved a remarkable increase in stature over the last decade—with Canadian researchers capturing a growing number of high-profile research awards and our communities building strengths in areas that are at the leading edge of mathematical and statistical sciences research. Our universities have been highly successful in building world-class research teams through the Canada Research Chairs program and other recruiting efforts. Canada is both a sought-after research partner and an attractive destination to study mathematical or statistical science.

This record of achievement and investment is a credit to Canada's diverse and dynamic research and professional communities in mathematics and statistics. Although precise numbers are difficult to obtain, we estimate that as many as 17,000 Canadians work as professionals in mathematics, statistics and actuarial science.[2] These include academic researchers—the main focus of this LRP—as well as mathematicians and statisticians working across an array of fields in industry, government and non-governmental organizations.

The other good news is that Canada's mathematical and statistical sciences communities are growing. University enrolment has jumped in the last decade in both mathematics and statistics as demand for specialists across the economy and

Snapshot of Canada's Research Community

University Departments

- 64 Mathematics and Statistics departments
- 6 additional Statistics departments in Medicine (5) and Business (1)
- 1400 faculty members

Mathematical Sciences Institutes

- Centre de recherches mathématiques (CRM)
- Fields Institute for Research in Mathematical Sciences (Fields)
- Pacific Institute for the Mathematical Sciences (PIMS)

Mprime Network of Centres of Excellence (NCE)

Banff International Research Station (BIRS)

Professional and Other Associations

- Canadian Mathematical Society (CMS) – 1000 members
- Statistical Society of Canada (SSC) – 1000 members
- Canadian Applied and Industrial Mathematics Society (CAIMS) – 350 members
- Atlantic Association for Research in the Mathematical Sciences (AARMS)

2 National Occupational Classification 21-61 is "Mathematicians, statisticians and actuaries." It is difficult to find employment data for this depth of classification, but Service Canada provides estimates for Quebec, which we combined with census information to estimate the corresponding number for Canada.

Our Vision

Canada will be a world leader in the mathematical and statistical sciences, and a driving force in interdisciplinary research and innovation that contributes solutions to important Canadian and global challenges.

academia in these fields has skyrocketed. Between 2000 and 2010, mathematics enrolment soared by 54 per cent at the master's level, 109 per cent at the doctoral level and 136 per cent at the post-doctoral level. In statistics, growth over the same period was also spectacular: 99 per cent at the master's level and 88 per cent at the doctoral level. This contrasts with more modest growth among Canada's general student population: a 2011 report from the Association of Universities and Colleges of Canada found that between 1980 and 2010, the undergraduate student body increased at an annual rate of 2 per cent while at the graduate level it grew by an annual rate of 3 per cent (Association of Universities and Colleges of Canada, 2011). Statistics Canada's data shows an increase of 70 per cent in second cycle (master's) and 48 per cent in third cycle (doctoral) postgraduate education from 2000 to 2009 (Statistics Canada, 2012).

Our Vision for Canadian Mathematics and Statistics

The 21st century looks auspicious for the mathematical and statistical sciences. Many of the "big questions" of mathematics are spinning off new theoretical breakthroughs and significant applications, as well as suggesting new challenges for future exploration (see Chapter 2). Some of the world's most talented people are studying or practising mathematics and statistics. Both sciences are bursting with ideas as the borders between mathematical and statistical sub-disciplines are falling away, and concepts and research questions from across the general sciences are rapidly being exchanged and used to build upon each other. Add to this the ever-evolving range of high-power computational and graphical tools now available to the research community, and breakthroughs in almost any area of the mathematical and statistical sciences are possible.

All this is bringing the mathematical and statistical sciences new recognition as sources of innovative thinking and fresh ideas. In a world increasingly characterized by complexity, the ability to tease apart difficult problems and work with multifaceted systems will be vital. Mathematical and statistical scientists—in Canada and abroad—have the expertise and the advanced theoretical and computational tools available to develop, evaluate and implement creative solutions to many of the world's most pressing problems. The capacity to work in

interdisciplinary teams at the intersection of existing and emerging streams of innovation, science and technology will be the key to realizing this potential.

Canadians are well placed to make important contributions to the evolution of the mathematical and statistical sciences at the international level—both by pushing the boundaries of pure mathematics and theoretical statistics, and by excelling in linking these ideas to the grand challenges that will define human progress in the 21st century. Our communities of researchers have the vision, talent and expertise to achieve international excellence in leading-edge interdisciplinary research and innovation.

Canada is a world leader in integrating mathematical and statistical expertise into interdisciplinary teams. Our universities and mathematical sciences are at the vanguard of harnessing the potential of the mathematical and statistical sciences to model and test solutions in areas as diverse as the life sciences, climate studies and materials research. Mprime (formerly Mitacs[3]) and other collaborative initiatives have built a strong capacity for interdisciplinary work with industry and other sectors of society.

Our goal for our communities over the next five to ten years is to build on this expertise to bring mathematics and statistics to the fore in finding solutions to issues that really matter to Canadians and to the world, from energy to security to environment to health care.

Opening the Doors to Discovery and Innovation—Three Fundamentals

Achieving our communities' vision will require a strong commitment to continued investment in mathematical and statistical sciences research, and a willingness to find new ways to collaborate with Canada's research community and its funders.

Our vision for building this capacity rests on three fundamental pillars:

- **People** Ensuring Canada's researchers are among the best in the world, and that Canada has the highly qualified personnel available to meet the demand for the mathematical and statistical sciences in a knowledge economy and complex society.
- **Research and discovery** Maintaining a vibrant, world-class, basic and applied research base that can drive discovery and innovation.
- **Innovation and connections** Fostering innovative approaches that advance interdisciplinary research, embed researchers in industry, and facilitate the flow of ideas between researchers and their potential partners across science, industry and government.

3 Prior to May 16, 2011, the Network of Centres of Excellence (NCE) in the mathematical sciences was known as MITACS Inc. Effective May 16, 2011, the mathematical sciences NCE assumed the name Mprime Network (Mprime Network © 2011). In this document, we use Mprime for convenience to refer to the NCE both before and after the restructuring in 2011.

Canadian Mathematical and Statistical Sciences Research

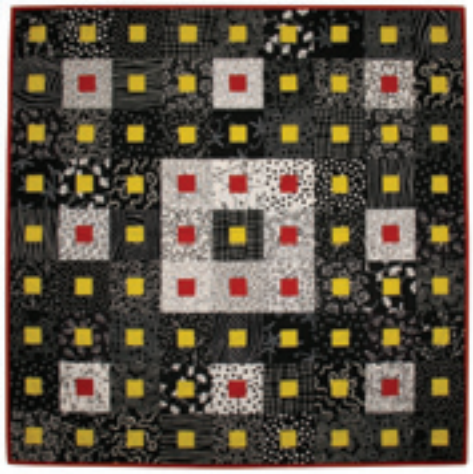
For Canada to have the mathematics and statistics capacity it needs to advance discovery and innovation over the coming decade, all three of these fundamental pillars must be robust and be well connected to each other.

No one pillar works in isolation. Incorporating new media and contemporary educational techniques into our teaching programs will expand the horizons of the next generation of researchers and equip them to work effectively in inter-disciplinary teams. Priming the research pipeline will generate new knowledge and ideas that attract opportunities for innovation and talented students to the field. New approaches that link the mathematical and statistical sciences with interdisciplinary research projects or industrial challenges will open new avenues for theoretical exploration.

This LRP describes the current environment that cuts across all three of these pillars and makes interrelated recommendations aimed at strengthening all three.

Implementing the Vision—Strengths and Opportunities

Canada is in a strong position to make this vision a reality for mathematical and statistical sciences research. First and foremost, our mathematical and statistical sciences communities are noted for their strength across a broad range of sub-disciplines. Canada is an acknowledged world leader in many areas of mathematics and statistics, including representation theory, number theory, statistical theory and foundations, probability theory, dynamical systems, algebra and combinatorics, geometry and topology, and partial differential equations. Equally important are our acknowledged strengths in more applied disciplines such as mathematical biology, quantum computing, cryptography, stochastic modeling, fluid dynamics, epidemiology, computational statistics, environmental statistics, statistics for medicine and population health, and theory and methods for survey sampling.



This range of excellence provides a strong foundation for advancing Canadian mathematics and statistics on the international stage, and for tackling global challenges through meaningful and respected interdisciplinary and applied research.

Other strengths in support of our communities' vision include:

- **A strong network of mathematical sciences research institutes that are both national and international in scope and calibre** CRM, Fields, PIMS, together with the Atlantic Association for Research in the Mathematical Sciences (AARMS) and the Institut des sciences mathématiques du Québec (ISM), have developed a variety of collaborative opportunities that have made Canada an acknowledged world leader in interdisciplinary studies. They have helped put Canada on the map as a leader in facilitating global and local progress in some of the hardest problems in the mathematical sciences.
- **A unique Canada / US / Mexico joint initiative hosted by Canada** The Banff International Research Station offers mathematical and statistical scientists from all over the world a secluded environment, accommodation, and the necessary facilities for intense, uninterrupted, scientific interactions and the exchange of ideas, knowledge and methods.
- **The most successful of Canada's Networks of Centres of Excellence** Mprime engages the mathematical and statistical communities, among others, with the needs of Canadian society. For the past 13 years, Mprime has played a defining leadership role in developing new models for academic-industry interactions, for training the next generation of researchers, and for opening channels for technology transfer.
- **Leadership on international projects connecting the mathematical and statistical sciences to global issues** Canada is a driving force behind Mathematics of Planet Earth 2013 (MPE2013)—a project that will promote applied scientific projects and outreach activities around the world. Canada's mathematical sciences institutes—together with the Banff International Research Station and Mprime—were key players in the National Science

Foundation-sponsored 2010–2011 Climate Change and Sustainability initiative, through which 14 North American mathematical sciences institutes combined forces to examine sustainability issues as diverse as economic modeling, infectious diseases and forestry management.

- **A strong research legacy from the National Program in Complex Data Structures (2003–2009)** Collaborations through the National Program in Complex Data Structures (NPCDS) developed statistical leadership, created new techniques and opportunities for interdisciplinary research, and created research teams linking researchers in academia, government and industry. This activity is being reinvigorated with the new proposal for the Canadian Statistical Sciences Institute.
- **A growing student population—particularly at the graduate and post-doctoral level** As noted earlier, enrolment in mathematics and statistics is growing at a phenomenal rate. These new students are also increasingly interdisciplinary in orientation, with more and more students exploring areas such as mathematical biology, finance and scientific computing each year.
- **A relatively young university faculty in the mathematical and statistical sciences** In mathematics, half of all current faculty have been hired in the last 10 years. Over the same period, the number of faculty in our statistical science departments has grown by 25 per cent.
- **The international character of Canada's mathematical and statistical sciences research communities** Of the 48 Canada Research Chairs in mathematics, 23 moved to Canada from abroad. This helps to bring not only the very best minds to Canada to conduct research and train the next generation of talent, it paves the way to further increases in Canada's already high international collaboration rate in the mathematical and statistical sciences.

Actuarial Sciences

Canada has a long and proud tradition in mathematics for insurance and investment. A recent study of research output in actuarial science noted that Canada's rank (worldwide) has moved from 8th to 3rd place over the past 10 years, and now ranks behind only Switzerland and Belgium in overall research output per capita (Genest and Carabarín-Aguirre, 2012).

Going Forward—Areas for Improvement

Canada's researchers in the mathematical and statistical sciences have the expertise, drive and momentum to bring real innovation to the most challenging and complex problems of importance to Canada and the world. However—despite these considerable strengths—there are challenges that may limit Canada's ability to move our vision forward.

Canada has forged a record of high achievement in the mathematical and statistical sciences with comparatively modest investment in international terms. As we describe in later chapters, the research community has been resourceful in leveraging the basic support it receives from the federal government with funding from other sources, including the private sector and international funding agencies. Nevertheless, current gains and future advances will be in jeopardy without further and continued investment in Canada's mathematical and statistical sciences research capacity.

Canada's funders of science, technology and innovation must remain fully committed to maintaining a strong capacity in mathematical and statistical sciences research and training if we are to have ready access to the talent, knowledge and

innovation we will most certainly need to sustain a strong economy in the years to come. In a globally networked society and economy—one characterized by intense competition for the very best talent—we cannot expect to have this level of innovation capacity on call unless we invest in the research infrastructure and people we will need for the future.

Already, there are signs of strains and shortfalls, both in the Discovery Grants system and with the ending of the Mprime NCE. Demand for skilled researchers and instructors is outstripping supply in our universities, as our faculty attempt to provide training in the mathematical and statistical sciences for the next generation of scientists, engineers and business professionals. Opportunities for groundbreaking interdisciplinary research are in danger of falling through the cracks because our funding structures have yet to find effective ways to support this new research reality.

These issues and others will need to be addressed in a sustainable, equitable and transparent fashion if Canada is to maintain, let alone grow, the mathematical and statistical sciences capacity it needs to be an innovation leader in the 21st century.

Priorities for the Next Decade

This Long Range Plan is the first of its kind for the mathematical and statistical sciences research community in Canada. It is the product of more than a year of consultation and discussion within our communities. It is also informed by the Government of Canada's Science and Technology strategy: *Mobilizing Science and Technology to Canada's Advantage.*

The LRP outlines the vision from our communities to strengthen Canada's research performance at the international forefront of the mathematical and statistical sciences and to augment Canada's capacity for interdisciplinary research that involves these foundational disciplines. Our communities see an important role for Canadian mathematical and statistical sciences in finding solutions to domestic and global challenges.

Critically, the plan also highlights the need to maintain the diversity of mathematical and statistical sciences research. It does not identify priority projects or sub-disciplines. Maintaining the breadth and diversity of scientific exploration is basic to the health of mathematical and statistical research. It is also vital to growing the capacity to support interdisciplinary and applied research. Our science base must have the agility to respond to emerging scientific, industrial and societal needs. It is impossible to accurately predict where these needs might arise. It is a strategic necessity to keep the basic research pipeline open and flowing in order to meet future needs for innovation in the mathematical and statistical sciences and the sciences that rely on their findings and advances. This means actively supporting both pure and applied research.

In the next chapters we describe some achievements of mathematical and statistical sciences research, discuss our research funding for people, discovery and

innovation, and detail the opportunities and the challenges for research funding over the next five to ten years.

Recommendations

The following recommendations outline the key directions and areas for investment identified by the LRP Steering Committee. More detailed recommendations are made in Chapters 3 through 7, and the complete list of recommendations is presented in Chapter 8.

- Invest in Canada's mathematical and statistical sciences research via Discovery Grant levels that reflect the importance of the research base to Canada, and that acknowledge that the costs of research are similar to those in several related science and engineering disciplines.
- Invest in Canada's network of thematic and collaborative resources in the mathematical and statistical sciences, including the newly developing Canadian Statistical Sciences Institute, and ensure that the funding envelope has a boundary between Discovery Grant funding and funding for these resources, to enable both to flourish and support each other.
- Augment the funding envelope to include the Research Partnerships Portfolio, enabling the mathematical and statistical research communities—working through the research institutes and Mprime—to provide a platform for a wide range of successful partnerships between the mathematical and statistical sciences and industrial partners.
- Establish a committee of leading mathematical and statistical scientists, chosen in consultation with the research communities, to oversee the implementation of this LRP, represent the research communities to NSERC, and develop research linkages among the mathematical and statistical sciences and allied science disciplines.

Uncovering the Heart of Mathematics

Dr. James Arthur
Pure Mathematics – Langlands program
University of Toronto


Courtesy of James Arthur

"Mathematicians—even if they are not fully conscious of it—see mathematics as something very much like the physical world. It's like you are an archeologist and there was a great civilization that was lost. You can just see the little tips of the pyramids that were built, and you are blowing away the sand bit by bit. At an intuitive level, you are looking for patterns. You are working with the faith that there is something there, but you have to look for little hints as to how you might figure out the structure that is completely invisible to you."

James Arthur is one of Canada's foremost pure mathematicians. Internationally renowned for the general trace formula and for his leading-edge research in an area known as the Langlands program, Arthur was elected a Fellow of the Royal Society of London in 1992 and a Foreign Honorary Member of the American Academy of Arts and Sciences in 2003. He is the only non-American to have held the position of President of the American Mathematical Society. He received the Gerhard Herzberg Canada Gold Medal for Science and Engineering—the highest honour in Canada for a scientist or engineer—in 1999.

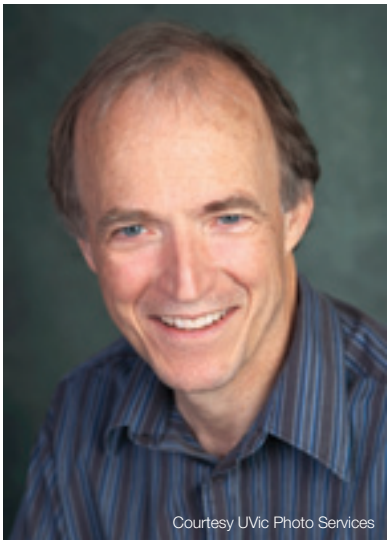
The Langlands program goes right to the heart of mathematics. Considered one of the most challenging areas of theoretical mathematics, it tries to establish the relationships between different streams of classical mathematics—some of which go back 100 to 200 years.

Arthur is best known for his discovery of the general trace formula. It is thought that this complex formula carries the means for establishing how all the different areas of mathematics that are part of the Langlands program relate to each other. Building on Atle Selberg's original work on the trace formula, Arthur discovered a complex formula that would work in all generality—or many situations. Since then, Arthur has continued to develop his trace formula, applying it to different problems. His latest monograph promises to be his most influential, tackling challenges that previously have been out of reach. Already available, in part, on his website, it is expected to change the playing field for many of the 500 people working on the Langlands program worldwide.

"Even if it doesn't solve the most basic question—known as the functoriality problem—it will change the landscape. It seems clear at this point that the trace formula will be the key to the eventual resolution of the Langlands program."

Predicting the impact of mathematical discoveries is difficult. Within mathematics, solutions to complex problems often wait for discoveries to be made in completely unrelated sub-disciplines. In the real world, pure mathematics can also find application in surprising ways. Telephone companies have already picked up the Selberg trace formula for network management. And the latest Arthur trace formula? With computer hackers a constant challenge to global communications and information systems, James Arthur expects to see it used someday in advanced cryptography to protect the integrity of future networks and databanks of all kinds.

"… At an intuitive level, you are looking for patterns. You are working with the faith that there is something there, but you have to look for little hints as to how you might figure out the structure that is completely invisible to you."


Courtesy UVic Photo Services

Making Sense of Our Changing Climate

Dr. Francis Zwiers
Statistics and Climatology
University of Victoria

"The interaction between statistics and climatology—especially in the last five years—has become closer and more dynamic. Climatologists are starting to use substantially more sophisticated tools than in the past. Statisticians are trying to push the statistical tools further to be able to solve these kinds of climatological problems."

Francis Zwiers is one of the world's leading experts in using statistical techniques to understand climate change and variability. In 2007, he was among the group of Canadian scientists who shared the Nobel Peace Prize that was awarded to the Intergovernmental Panel on Climate Change (IPCC), jointly with Al Gore. A Fellow of the Royal Society of Canada and the American Meteorological Society, he has received numerous awards, including the Statistical Society of Canada's Impact Award (2011) and the World Meteorological Organization's Award for Exceptionally Long Term Service to the Commission for Climatology (2010).

"… sophisticated new techniques from statistics are starting to find their way into real-life applications—this is very exciting for climate research."

Climate models are built on the laws of physics and describe the motion of the atmosphere and ocean using complex systems of mathematical equations. They are used to simulate both historical and potential future climate change and variability, with a view to providing information on the causes of past climate changes and the potential climate of the future to which society may have to adapt. However, using the output from climate models is not easy, due in part to the amount of data generated. Climatologists therefore make extensive use of statistical techniques to analyze and synthesize both observed and simulated climate variability.

Zwiers is currently involved in applying new statistical tools—such as extreme value analysis and statistical downscaling—that can improve our understanding of extreme weather events. Extreme value analysis has become a "hot" topic within climatology and the statistical sciences, with potential applications to risk management in sectors as diverse as finance, transportation and resource management. In climatology, the possibility of predicting changes in the occurrence of extreme weather and climate events is increasingly important for industry and government as they seek to anticipate the impacts of climate change. For example, building engineers need to be sure that the houses they design can withstand the weight of extreme snowfalls, such as a 100-year snowfall event. Hydroelectric companies want to anticipate future water levels to plan for adequate supplies of hydro power. Mining companies want to understand hydrological patterns in order to safely store mine tailings over long-term planning horizons. The ability to model scenarios like these is essential to minimize risks to public safety and to the environment, as well as to ensure the smooth functioning of society.

"Some of the new statistical techniques have become feasible with increases in computing power and the development of algorithms that can efficiently calculate high-dimension numerical integrals. For this, and other reasons, sophisticated new techniques from statistics are starting to find their way into real-life applications—this is very exciting for climate research."

CHAPTER 2

A New Era for the Mathematical and Statistical Sciences

Overview

Many see the 21st century as a time of great potential for the mathematical and statistical sciences around the globe. Both sciences are enjoying an unprecedented period of discovery and influence as new computational tools combine with new ideas to generate important breakthroughs and recognition. The contributions of the mathematical and statistical sciences are being welcomed by the world of science and technology—and beyond—like never before.

It is also an exciting time on a professional level for many mathematicians and statisticians—as new research paradigms open up new opportunities to ignite their passion for scientific exploration and collaboration. This stimulating environment is attracting a new generation of researchers and practitioners, and reshaping our research enterprise.

A Golden Age for the Mathematical and Statistical Sciences

The first decade of the new millennium has been witness to a substantial jump in the rate of mathematical and statistical discovery. A vibrant and growing research community worldwide is generating an escalating number of mathematical proofs and publications. However, these gains are not just about a rise in intensity, they are also about impact—the growth in output has been accompanied by a seeming rise in the number of significant breakthroughs in mathematics and statistics. In mathematics, the proof of the 100-year-old Poincaré conjecture and the Green-Tao proof of arbitrarily long arithmetic progressions have received widespread attention, but other advances have also altered the scientific landscape.[4] From electronic commerce to neuroscience to materials science, a mathematical wave of discovery is sweeping the shores of science and technology (Everhart, 2011).

The rapid dissemination and translation of many of these findings into innovation and application is also notable. As an example, in 2011, the U.S. National Academies' committee on Mathematical Sciences in 2025 pointed to the dramatic speed with which the theorems of Donoho, Candès and Tao on compressed

Compressed Sensing and the Lasso

Most images and signals we gather are compressed before scientists use them for discoveries. Our digital cameras compress images even before we see them. Compressed—or compressive—sensing turns this around and asks "how can we best design sensors that compress the data *while* it is being gathered?" As just one example, advances in compressed sensing enable high-quality MRI scans to be obtained in seconds instead of minutes (Lustig, 2007). The theory of compressed sensing uses, among other technologies, a statistical technique developed in Canada in the mid-1990s called the "lasso" (Tibshirani, 1996). This technique was not initially widely adopted; computation then was much slower, and large data problems were more rare. In recent years, the lasso has found thousands of applications in statistics, computer science, engineering and signal processing, and compressed sensing is undergoing an explosion of activity that ranges from new mathematical theories to new measuring instruments.

4 Proudly, the Green-Tao theorem was proved when Ben Green was a post-doctoral fellow at PIMS.

Crossing Boundaries

In algebraic geometry, the concept of mirror symmetry is used to uncover hidden relations between spaces that are seemingly unrelated. This principle has made it possible to solve long-standing classical problems. It is most remarkable that mirror symmetry first came up as a heuristic principle in high-energy physics, to calculate quantities that were out of reach with traditional techniques. Much remains to be understood from a mathematical perspective, but the impact of mirror symmetry on both algebraic geometry and physics has been immense.

The field of algebraic geometry has been applied to problems as varied as statistical analysis of social networks, development of new algorithms for computational biology, and statistical disclosure limitation, which ensures that government-funded surveys can be used for further research without compromising privacy.

sensing were used to develop new imaging equipment that could significantly outperform existing standards. "Just three years after publication of their ideas in 2004, compressed sensing was named by *Technology Review* as one of the top ten emerging technologies of 2007" (Everhart, 2011). The appetite for mathematical discovery across science, industry and society is almost unparalleled.

In statistics, the development of new methods, rather than proofs of new theorems, is the main currency. However, here too, the rising demand for statistical methods across science and society is unprecedented. Statistical science is an essential partner in some of the grandest scientific and technological undertakings of our time. A quick roll call includes:

- developing methods for analyses of massive data sets in the physical sciences, from the Large Hadron Collider at CERN (the European Organization for Nuclear Research) to the Sloan Digital Sky Survey;
- enabling the bioinformatics revolution of genomics, proteomics and metabolomics;
- advancing the development of artificial intelligence; and
- making sense of all "things" environmental—from interpreting climate data and extreme weather events to modeling ocean currents and changing populations of commercial fish stocks.

A Changing Research Landscape

As with all sciences, the mathematical and statistical sciences are very much part of a changing research landscape—a fact that is amplifying many of the trends mentioned above. Scientific convergence, globalization and other developments are changing the way mathematicians and statisticians often work, and influencing the kinds of challenges they choose to work on. Many mathematicians and statisticians—and their research institutions—are at the vanguard of creating new research and training models, and are driving discovery not just in the mathematical and statistical sciences, but across the social sciences, life sciences, physical sciences and engineering.

It is noteworthy that in the *The State of Science and Technology in Canada, 2012* report (Council of Canadian Academies, 2012), mathematically related research areas are identified as sub-fields in several fields other than Mathematics and Statistics. In the field of Information and Communication Technologies, both the sub-fields Computational Theory and Mathematics, and Artificial Intelligence and Image Processing, have strong mathematical and statistical components, as do Econometrics (a sub-field of Economics and Business) and Bioinformatics (a sub-field of Enabling and Strategic Technologies).

Integration The boundaries within mathematics are blurring as discoveries in one area are picked up and used in another. The unity of mathematics has always been a singular feature of the science. However—as discussed in Chapter 1—many recent mathematical advances have exhibited an unprecedented

crossover of ideas within the sub-disciplines of pure mathematics, as well as between pure mathematics and the many streams of applied mathematics and statistics. Algebraic statistics is just one example of a new field using abstract algebraic techniques to understand complex dependencies in discrete data. The distinction between "theoretical" and "applied" research and activities is no longer straightforward.

In the past, many areas of pure mathematics were developed by single or very small groups of researchers working on problems in "invisible colleges." The increase in the number of mathematical sciences institutes worldwide and the increasing availability of online collaborative tools has made these invisible colleges visible.

Interdisciplinary collaborations Another key feature of the changing landscape is the rise of interdisciplinary science and collaborations. Applied mathematics and statistics are richly informed by practical application and are in demand for collaborative investigations of all kinds. Biostatistics has a long history of motivation by, and collaboration with, research in medicine and population health. Fields with names such as astrostatistics, computational biology, chemometrics, percolation theory, geophysical fluid flow and geomatics reflect the symbiosis between science and mathematics and statistics.

Research pace The pressure to rapidly develop, publish and apply results is being felt across much of the global scientific enterprise. Mathematical biology and computational biology, in particular, move extremely quickly and researchers are actively embracing the latest computational, collaborative and communication tools to keep pace with their colleagues around the world.

"Probability theory at one end melds into discrete mathematics and at another into financial mathematics. An expert in partial differential equations can use some computational tools in his or her work, or at the other end tie into number theory."

Canadian Mathematical Society, 2011

Millennium Prize Problems

The Millennium Prize Problems highlight some of the most fundamental questions in mathematics:

- P versus NP problem
- Hodge conjecture
- Poincaré conjecture (solved in 2002–2003)
- Riemann hypothesis
- Yang-Mills existence and mass gap
- Navier-Stokes existence and smoothness
- Birch and Swinnerton-Dyer conjecture

Computational paradigms Advances in computational science, and the increased accessibility of high-performance computing are revolutionizing applied mathematics and statistics. As the Statistical Society of Canada highlighted in its brief to the LRP Steering Committee, "Models are larger and more complex, methods are more iterative and more highly computational, and often more exploratory" (Statistical Society of Canada, 2011). In the case of the statistical sciences, these trends are causing a redirection of research, practice and methods. Computational tools, software and empirical analysis now frequently supplement more traditional mathematical statistics and asymptotic theory.

The science of complexity The process of managing complexity in science and technology, industry and society has led to what some are calling the new "science of complexity." In the words of the European Mathematical Society, "Together with theory and experimentation, a third pillar of scientific inquiry of complex systems has emerged in the form of a combination of modeling, simulation, optimization and visualization. In most of the cases, complex phenomena cannot be replicated in the laboratory" (European Mathematical Society, 2011). The mathematical and statistical sciences are very much at the forefront of this new method of inquiry that crosses traditional disciplinary boundaries and generates fresh ideas that are transforming scientific, engineering and managerial practices in business and government. Many consider mastery of these new research processes to be critical to maintaining a competitive edge in the international scientific enterprise and global marketplace.

Industrial partnerships The last decade has seen the rise of closer links between industry and academic mathematicians and statisticians. Canada has been at the forefront of this international phenomenon. The highly successful Mprime Network of Centres of Excellence (NCE) introduced a new culture of interdisciplinary research that connected mathematicians with industry and put innovation firmly on the agenda of Canada's mathematics and statistics communities. Many university researchers have embraced the idea that their work can also find an outlet in an industrial setting.

"New applications in high frequency trading, actuarial science, genomics, biostatistics, genetics, machine learning, climatology, etc. were as unforeseen 25 years ago as the next breakthroughs are today."

Statistical Society of Canada, 2011

The Big Questions in Mathematics

Trying to predict the future is never easy. This is especially the case in science, where discoveries and innovation often emerge in surprising ways. Researchers in mathematics and statistics are generally reluctant to try to predict the next big breakthrough because both sciences are so diverse and the questions they tackle are often interrelated. Nevertheless, there is some consensus around broad areas that are likely to inspire and fuel research in the mathematical and statistical sciences over the coming decade.

In 2000, the Clay Institute in Cambridge, Massachusetts identified seven fundamental problems in mathematics for the new millennium, challenged the world's researchers to solve them, and offered a prize of $US1 million for each solution. These Millennium Prize Problems have raised general awareness of the open frontier of unsolved problems that remain in mathematics. The program echoes a similarly influential list of 23 unsolved problems first presented by German mathematician David Hilbert at the meeting of the International Congress of Mathematicians in 1900.

Of the seven Millennium Prize Problems, only the Poincaré conjecture has been solved so far. Grigoriy Perelman—a Russian mathematician—developed the solution in 2002–2003, and was awarded the Fields Medal in 2006 and the Millennium Prize in 2010.

Synergies with Strategic Growth Areas

A number of strategic growth areas within science and technology—areas of international and national importance—are embracing the mathematical and statistical sciences at new levels. Many of these also reflect the growing relationship between the mathematical and statistical sciences and society as a whole.

Canada's mathematical and statistical sciences communities aim to be at the forefront of international work on the grand challenges associated with connecting mathematics and statistics to these growth areas. This will require leadership and collaboration with partners across science, industry and government.

Large data sets Scientists, social scientists, financial markets, health care organizations, policy groups, government and industry are faced with overwhelming amounts of data, and subfields of nearly every discipline have developed around the need for extracting information from very large amounts of data. Data mining—now a necessity for modern progress in many areas—relies upon innovation and development in statistical and computer methods. "Massive and complex data are here to stay and provide a diverse set of opportunities for both theoretical and applied areas of computational, mathematical, and statistical sciences" (Pantula, 2011). From 2003 to 2009, Canada had a successful program to tackle the challenge of "big data"—the National Program for Complex Data Structures (NPCDS). The loss of this program left a gap in infrastructure support for collaborative partnerships between statistical scientists and subject-matter researchers. In response, the statistical sciences community has prepared a proposal for the new Canadian Statistical Sciences Institute to join the cluster of thematic and collaborative resources in the mathematical and statistical sciences.

Image analysis Our ability to process and manipulate data makes the mathematical and statistical sciences a powerful lens for sensing the physical world around us. Medical imaging, signal processing and remote sensing play an increasingly important role in subjects ranging from medical care to surveillance and security. All rely heavily on mathematical and statistical methods for

P Versus NP

The P vs NP problem is considered the most important open problem on the complexity of algorithms. It was introduced by University of Toronto theoretical computer scientist Stephen Cook in 1971. The problem asks whether questions exist that can be quickly verified (a given answer can be checked in polynomial time, *P*), but require an impossibly long time to solve (an answer cannot be obtained in polynomial time, *NP*). The extraordinary impact of the problem highlights the cross-fertilization of mathematics and computer science.

Stephen Cook is one of a distinguished group of Canadian mathematical scientists—including Donald Coxeter, Louis Nirenberg, Robert Langlands and James Arthur—working either here or in the US during the last 50 years who have had a profound influence on the most important current directions in mathematics.

Opportunities for Canadian Leadership

Connecting the mathematical and statistical sciences to strategic growth areas.

- Analysis of high flow data, geometry and topology of data sets
- Biomedical and image analysis
- Quantum information and computing
- Mathematics of materials (including nanomaterials)
- Sustainability analysis and the environment
- Mathematics of financial systems, financial engineering
- Analysis of epidemics, public health and mathematical biology
- Analysis of energy systems
- Information processing for global surveillance

constructing complex multidimensional images from sensor data. As sensing becomes more powerful, our algorithms for processing the increasing amounts of data must also improve and become more sophisticated. Mathematical and statistical scientists are challenged to create fundamentally new approaches and to develop new algorithms that connect closely to the work of scientists on the front line of imaging and sensing.

Quantum information and computing As classical computers begin to approach physical constraints that limit their increase in speed, new paradigms for computing are being developed. Quantum information computing aims to revolutionize information technology, with implications ranging from computer security to massive computation. Canada is a world leader in this field, led by Montreal's Institute for Transdisciplinary Research in Quantum Computing, the Institute for Quantum Information Science in Calgary and the Institute for Quantum Computing in Waterloo. Despite rapid progress in quantum computing, practical implementation of a quantum computer remains a major challenge, in which collaboration among mathematicians, computer scientists and engineers will certainly play a key role.

Materials and nanotechnology Mathematics can provide tools for designing a better physical world. Our requirement for specialized materials in energy, medicine and aeronautics means manipulating matter, often at atomic and molecular scales. The mathematical sciences are at the core of designing composite materials and nanomaterials—emerging priority areas in today's manufacturing economy. Canada has developed and promoted research in this area through the institutes of the National Research Council of Canada—the National Institute for Nanotechnology and the Industrial Materials Institute, among others—and maintains a globally competitive position.

To date, much of the research activity in Canada has focused on a suite of application areas, especially nanobiotechnology (Hu, 2011). The challenge for mathematicians is to help develop new mathematical theory that underpins materials. One fundamental question is how to construct optimal global structures by following simple local rules via the process of nanoscale self-assembly. Progress on this and on related problems will maintain Canada's edge and open new areas of research.

Sustainability Sustainability of the planet for a population of some 10 billion will require remarkable progress in science and technology. We need to further develop our ability to answer questions regarding environmental and climate change, resource availability and energy management (Rehmeyer, 2011). Because we have less room for error than in the past, we must develop methods that are better suited to understanding and specifying the uncertainties that we encounter. Some key areas where mathematical and statistical methods can make a difference include:

- predicting natural disasters, and planning how to respond to the resulting emergencies;

- understanding the economic issues that are interwoven with environmental sustainability, including calculating how much should be spent to protect an ecosystem or predicting the dynamics of carbon markets;
- determining the wise use of resources, such as water, and understanding the factors governing water use as well as pollution; and
- transforming our energy infrastructure and developing the tools to design efficient and innovative resource development methods, more robust power grids, and improvements to materials for applications ranging from solar cells to batteries to superconductors.

Canada has made great progress in addressing these questions using mathematical and statistical tools over the last two decades, facilitated by the Mprime NCE. The challenge is to find new mechanisms to connect the mathematical and statistical sciences with these critical application areas into the future.

Financial mathematics The kind of uncertainty experienced by natural systems in the environment is also present in man-made structures such as financial markets. Finance, energy, commodities, insurance and manufacturing are under pressure of competition and regulation, and consequently have rapidly growing needs for quantitative methods that can address complexity. Mathematical analysis has become a mainstay in the analysis of risk and return, and as financial systems evolve, so must the mathematical and statistical sciences used to understand them.

Canada has strong research groups in financial mathematics, specialized training programs, and a commitment to forging links with industry and government. Financial mathematics is a key area for young people; it has a tremendous number of untapped but accessible research topics, and excellent career options. The challenges include meeting the demand from students to work in the field, and maintaining research ties with an industry that by its very nature operates within very short time frames.

Mathematical biology As the current revolution in biological information-gathering progresses, there is a well-recognized need for new quantitative approaches and methods to solve problems in biology. The major challenge is to model complex biological systems—systems that depend upon a myriad of inputs, but often with incomplete details regarding their context. Here mathematical and statistical models have a central role to play in piecing together parts of the biological puzzle. In turn, models arising from the biological problems provide new and fertile ground for innovative mathematical and statistical analysis. The synergy between these fields is a driving force in the recent success and growth in mathematical biology. Results range from optimizing cancer therapy to controlling infectious disease outbreaks, and tracking and predicting the spread of harmful invasive species.

Canada is very much a part of this revolution in quantitative thinking in biology and is a significant world presence in the depth and breadth of its work. There are a number of very successful centres in mathematical biology in Canada,

several of which have been funded by Mprime. This is a field of explosive growth and great opportunity; mathematics and statistics are certain to play important roles. However, *which* mathematical and statistical ideas will emerge as most crucial is not yet known and perhaps not yet discovered. One natural possibility that has been discussed by the mathematical biology community is to work towards developing an NCE in mathematical biology.

What Does this Mean for Canada?

Canada has the opportunity to lead internationally on many of these big questions and strategic growth areas—bringing its proven strengths in statistics, applied mathematics and pure mathematics to bear on both fundamental science and the translation of discovery into innovation and application. The role of the mathematical and statistical sciences in developing vital tools and techniques for scientific research of all kinds is indispensable. It also seems certain that Canada will continue to push the edges of interdisciplinary research that includes mathematics and statistics.

For Canada to achieve these aspirations, *a vibrant research program in the mathematical and statistical sciences is essential.* However, it is difficult to predict which particular fields of mathematics and statistics will most guide innovation in the next decades. Indeed, all areas of the mathematical and statistical sciences have the potential to be important to innovation, but the time scale may be very long, and the nature of the link is likely to be surprising. Many areas of the mathematical and statistical sciences that strike us now as abstract and removed from obvious application will be useful in ways that we cannot currently imagine. Research programs in mathematics and statistics have a strong internal structure; they build on a rich legacy of mathematical discovery, and create a new legacy for the future. This sense of building part of a scientific edifice is both exciting and humbling.

On the one hand, we need a research landscape that is flexible and non-prescriptive in terms of areas to be supported. We must have a research funding landscape capable of nurturing a broad range of basic and applied research and that can take into account the changing characteristics of the research enterprise itself. And on the other hand, we need to build and maintain infrastructure that will connect the mathematical and statistical sciences to strategic growth areas—as outlined above—and will encourage effective technology transfer and innovation across science, industry and society.

It is these trends and certainties that have shaped our communities' vision for the coming years and the LRP Steering Committee's thinking on how to leverage Canadian mathematical and statistical sciences to contribute to the international research enterprise and to Canada's long-term economic prosperity and overall well-being.

Unlocking Quantum Cryptography

Dr. Gilles Brassard
Quantum Information Processing
Université de Montréal


Courtesy of Gilles Brassard

"Initially, in the 1980s, when my colleague, Charles Bennett, and I were first developing quantum cryptography, we were not taken seriously by the research community. Our collaboration started with a chance meeting at the beach. We just started talking and he told me he knew how to use quantum mechanics to make bank notes that were impossible to counterfeit. After about a half-hour, I had added my ideas, and we had the basis for what led us to invent quantum cryptography. It took years for our ideas to be accepted. Now quantum cryptography is mainstream."

Gilles Brassard is an internationally acclaimed researcher in computer science and the founder of the field of quantum information science in Canada. His many accolades include the Killam Prize in the Natural Sciences (2011), the Gerhard Herzberg Canada Gold Medal for Science and Engineering (2009) and the Government of Quebec's Prix Marie-Victorin (2000). He was elected a Foreign Member of the Academia Europaea in 2011 and a Fellow of the Royal Society of Canada in 1996.

Quantum cryptography takes advantage of quantum mechanics and the mathematics of information theory to transmit information in a way that ensures complete confidentiality, even if an eavesdropper has access to unlimited computing power and technology limited only by the laws of physics. Brassard's discoveries provide one of the few ways of protecting the world's communications and information systems against cyberattacks from quantum computers. Such a technological advance will be vitally important if the dream of quantum computing is ever to be fully realized. Quantum computing would be a revolutionary new technology for society. However, our global financial, security and communications systems will require a new level of encryption to protect their vast databases from improper use. Although classical cryptography may someday find the means for doing this, quantum cryptography has already demonstrated its capability. The theory is in hand, although it is difficult to predict how rapidly the infrastructure will be developed.

"I'm using mathematics as a tool to push the frontiers of physics and computer science."

Always an original thinker, Brassard is now asking deep questions about the nature of quantum mechanics itself—flipping his research on its head to make one of his tools the object of his inquiry. Our current understanding of quantum mechanics is the product of years of collective thinking, with one discovery building upon another. In Brassard's view, it is time to do a kind of "reverse engineering" of quantum mechanics that peels back the layers to validate its most fundamental truths. By applying this kind of rigorous thinking, he hopes the scientific community can develop a better understanding of how nature really works and open the door to new discoveries of all kinds. Again, he is taking a multidisciplinary approach, with information theory and computer science as part of his arsenal to unlock the mysteries of nature.

"I'm using mathematics as a tool to push the frontiers of physics and computer science."


Courtesy of Leah Edelstein-Keshet

Exploring Patterns—the Mathematics of Living Things

Dr. Leah Edelstein-Keshet
Mathematical Biology
University of British Columbia

"Mathematical biology is a huge field now—it's really exploded. It's very eclectic in the number of areas that it covers. I have colleagues that work on disease dynamics, vaccination strategies, the evolution of virulence, and much more."

Leah Edelstein-Keshet is one of Canada's leading researchers in mathematical biology. An early practitioner in this field that combines mathematical theory with biological and life sciences data, she is the author of a seminal text on the subject—Mathematical Models in Biology. As team leader of a Mitacs team on biomedical modeling of physiological processes and disease (1998–2008), she attracted some $1.5 million in public and private funding to study aspects of Alzheimer's disease and Type 1 diabetes. In 2002, she received the Canadian Mathematical Society's Krieger-Wilson Prize for outstanding research by a female mathematician.

"I've been working for many years on theoretical ideas of what is happening inside cells. But recently, I've been working with people who work on real cells to see what cells really do. The exciting thing is that by using real data, we can revise our models and discard assumptions that don't make sense. It works in both directions. The biologists finally have the tools to collect quantitative data. But they need help to decipher this data—a difficult thing to do without a framework to help understand what is going on inside various biological systems."

Much of Edelstein-Keshet's current research is on the chemical interactions that allow cells (such as white blood cells) to move inside the body. Gaining insights into cell motility—or movement—is an important step toward understanding how processes like wound healing work or how tumours metastasize and grow. How does mathematics come into play? Edelstein-Keshet uses sets of partial differential equations and mathematical theories relating to pattern formation to describe how chemicals interact with each other and diffuse inside a cell. It is these interactions that establish the difference between the front and back of a cell, and ultimately are responsible for polarizing a cell and selecting a direction of motility. Ultimately, the hope is that this information could be used in identifying drug treatments for cancer or various autoimmune diseases.

"We hope that the work will have an impact on research in cell biology, and we seek close collaborations with cell biologists. But also we hope it will have impact in applied mathematics. When we work on interesting problems from biology, we encounter situations in which some new mathematical ideas or new mathematical tools come up. Some of these have been published in applied math journals and have created interest with applied mathematicians. Other researchers can take these discoveries and go in other directions."

"Mathematical biology is a huge field now—it's really exploded. It's very eclectic in the number of areas that it covers. I have colleagues that work on disease dynamics, vaccination strategies, the evolution of virulence, and much more."

CHAPTER 3

Research and Discovery—People and the Pipeline

Overview

The long-term health of mathematical and statistical sciences research—and its ability to drive both discovery and innovation in Canada—depends on direct support of our researchers and on the training of highly qualified personnel to continue to develop this research potential. Maintaining this support—and ensuring that it delivers a broad, flexible research base in an effective manner—is essential to our communities' vision of achieving international excellence and contributing solutions to Canadian and global challenges. In this chapter, we describe the current landscape for research and training, discuss the challenges and opportunities as we move forward, and outline our ideas for success.

We have great opportunities for mathematical and statistical sciences research in Canada: demand for sophisticated techniques, for collaborations and for highly qualified personnel (HQP) has never been stronger. At the heart of this enterprise are our people: our academic researchers, post-doctoral fellows, graduate students and undergraduate students.

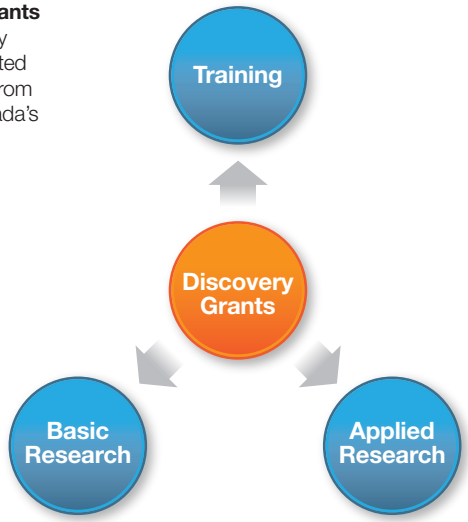
To develop our full research potential, we must exploit all the diversity Canada has to offer. Our sources of talent cut across geographic, cultural and gender lines, and we need to ensure that our research programs are sufficiently flexible to make the best use of this capacity. Research excellence in the mathematical and statistical sciences is also distributed across universities of varying sizes; in particular, smaller institutions form an important and vital part of the research ecosystem. Support for excellence in research and training must recognize the importance of both this breadth and depth.

Quantitative reasoning is now considered an essential ability for the knowledge economy and the digital world, and most universities are expanding their requirements to include quantitative analysis in all fields of study. The demand for such training shows no signs of slowing, and mathematical and statistical scientists are at the vanguard of its delivery. This can be seen in the increasing demand for undergraduate and graduate programs and courses in the mathematical and statistical sciences. The remarkable success of Mprime in placing students in industrial internships is further testament to the demand for quantitative skills in the marketplace.

> "In 2008, for example, Canada—with one half of one per cent of the global population—accounted for more than three per cent of scientific publications in the world… Our greatest renewable national resource is our grey matter."
>
> **The Honourable Jim Flaherty**, Minister of Finance, speaking to the Perimeter Institute's Innovation Nation Symposium, September 2011

Discovery Grants—The Engine of Discovery and Innovation

NSERC's Discovery Grants Program is internationally respected and has attracted world-class researchers from around the globe to Canada's universities



Our communities are actively engaged in this expansion of training and outreach at many levels—from Kindergarten through "infinity." While not the focus of NSERC-supported research, efforts to maintain a flow—or "pipeline"—of future researchers interested in training for, and pursuing, careers in mathematics and statistics impacts on our research programs in important ways. Our communities' future depends on recruiting, training and eventually hiring the best and the brightest. It is these researchers who will make the research discoveries that will power Canada's next level of innovation.

Investigator-driven research sits at the nexus of these expanding opportunities, feeding basic research, applied research and training. Investment in basic research has an immediate economic benefit through its link with training: we hear repeatedly from business leaders that analytical skills and the ability to acquire new knowledge are the most important qualifications for young hires. Investment in basic research has a long-term economic benefit through enabling technological innovation. This benefit is highly unpredictable in its specific aspects—the list of current technological advances that rely on what was once "curiosity-driven" research is long. What *is* highly predictable is that the next technological innovations will be built on basic research.

NSERC's Discovery Grants program is the funding engine of basic research for the mathematical and statistical sciences in Canada. The program's flexibility—and emphasis on investigator-driven research—is admired by scientists and engineers around the world, and has been so for many years. NSERC's international review of the Discovery Grants program in 2008 found that, "the Discovery Grants Program is an exceptionally effective model for supporting Canadian research in the NSE [natural sciences and engineering] fields… the philosophy and design of the [program] make it suitable not only for Canada's circumstances but also for those of university research environments in many other countries" (NSERC, 2008). As such, it has served as a magnet for attracting outstanding researchers to Canadian universities.

Landscape for Research Training

According to recent surveys of mathematics and statistics departments by the Canadian Mathematics Society (CMS) and the Statistical Society of Canada (SSC), graduate student enrolment in the mathematical and statistical sciences has nearly doubled in the past 10 years, while undergraduate student enrolment has grown some 20 per cent over the same period. Data from the CANSIM Database (Statistics Canada, 2012) combines mathematics and statistics with computer and information sciences, so direct comparisons are difficult. However, their data shows that from 2000–2001 to 2008–2009, enrolment in master's and doctoral programs increased by 52 per cent in all disciplines, by 45 per cent in the physical and life sciences, and by 61 per cent in mathematics, computer and information sciences. It is likely that the larger increase in mathematics and statistics was offset by the decrease in enrolment in computer and information sciences in the early 2000s. Our doctoral programs are attracting talented international students; in 2009 international students comprised 25 per cent of doctoral graduates in mathematics and statistics, against a national average in all fields of 11 per cent (Council of Canadian Academies, 2012).

While the reasons for this rising enrollment have not been fully analyzed, it seems to be a natural response to the wide range of challenging career paths now open to those with advanced knowledge and training in these areas. The mathematical, statistical and actuarial professions are consistently rated among the most satisfying jobs. In 2011, they were ranked 2nd, 3rd and 4th by JobsRated.com (Steber, 2011) in an analysis that compared 200 different professions for their work environment, stress, physical demands, income and outlook.

In spite of these increases, the number of students trained in the mathematical and statistical sciences is still not sufficiently large to meet the demand in this area. Canada—like the rest of the world—is facing an unprecedented demand for graduates with these skills. The Chief Executive Officer of the National Stock Exchange of India recently told *The Economic Times of India* (Kuvda, 2011) that, "as the amount of data companies and governments are collecting continues to multiply exponentially, the ability to 'leverage the big data' and extract wisdom from it will be a crucial talent and skills issue." This CEO was speaking to a global trend that is just as significant for Canada as for any other nation. Similarly, a CIHR discussion paper in 2010 reported that, "most academic health science centres conducting clinical research report a critical shortage of biostatisticians and methodologists" (Canadian Institutes of Health Research, 2011).

"Humans are now making significant progress in understanding how to fly, control, and land flapping-wing aircraft… surprisingly, the most novel technology behind the perching glider was a… beautiful mathematical device called Lyapunov functions" (Mackenzie, 2012). The Russian mathematician Lyapunov developed this "device" in his 1892 doctoral thesis.

Training and Outreach

The Department of Statistics at the University of Toronto has launched a course for humanities students called "Why Numbers Matter." This offering responds to new breadth requirements for quantitative literacy in the Faculty of Arts and Science.

In 2010, the semi-annual magazine *Accromath* for students in high school and CEGEP, published by the Centre de recherches mathématiques (CRM) and the Institut des sciences mathématiques du Québec (ISM), received special mention for the Prix d'Alembert, from the Société mathématique de France.

Blurring Boundaries

Differential geometry and probability, traditionally quite separate spheres, have together created spectacularly successful new tools for the analysis of images in fields ranging from neurology to astrophysics. Differential geometry has also turned out to be fundamental to a theoretical understanding of many statistical models.

Landscape for Research Excellence

As mentioned in Chapters 1 and 2, the research landscape for the mathematical and statistical sciences—both globally and in Canada—has changed considerably since 2000.

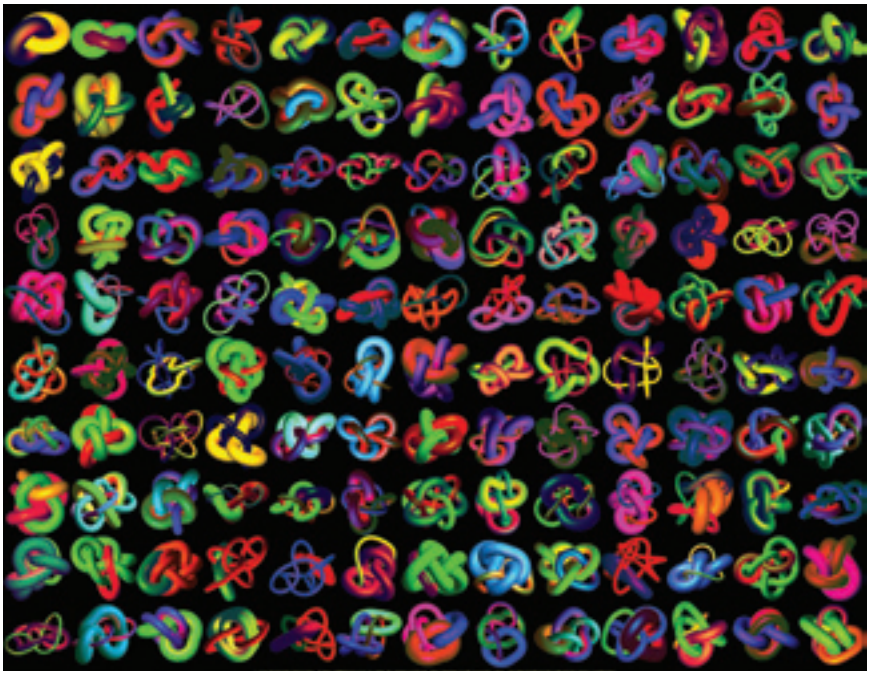
The 2010 survey by the CMS notes that more than half the faculty members in departments of mathematics have arrived in the past 10 years—with the Canada Research Chairs program enabling the recruitment of many outstanding senior and junior leaders. While the growth in faculty has been concentrated in larger universities, this renewal has brought new energy to all universities. And smaller departments have increased their research profile quite dramatically.

At the same time, research in the mathematical sciences has become much broader and more collaborative. "Not only has applied mathematics grown explosively in recent years, but also many mathematical subdisciplines have broadened out their remit into both pure and applied mathematics… Indeed, the full pure-applied spectrum is often exhibited in single researchers, with for example, one whose web page exhibits papers both in holomorphic dynamics and in mathematical biology" (Canadian Mathematical Society, 2011).

In the statistical sciences, research advances have always been strongly linked to collaboration with other disciplines, but the range and diversity of substantive areas seeking statistical expertise and collaboration continues to expand. Faculty numbers at Canadian universities increased by about 25 per cent between 2000 and 2010, reflecting the increased demand for research and teaching in statistical sciences that is accompanying the data explosion in other fields of research. Graduate student enrolment over the same period of time has doubled, although the post-doctoral program in statistics remains relatively small. This is partly a function of the strong demand for statistical science PhDs—both in academic and in non-academic positions—and partly a reflection of the limited resources available for post-doctoral fellowships in the statistical sciences.

"The ability to take data—to be able to understand it, to process it, to extract value from it, to visualize it, to communicate it, is going to be a hugely important skill in the next decades, not only at the professional level but even at the educational level for elementary school kids, for high school kids, for college kids; because now we really do have essentially free and ubiquitous data. So the complimentary scarce factor is the ability to understand that data and extract value from it."

Hal Varian, Chief Economist at Google (McKinsey & Company, 2009)



Research Funding for Training HQP

Support for training the next generation of researchers comes from a variety of funding mechanisms in Canada, including grants to individual investigators. These provide important opportunities for students and early-career researchers to gain hands-on experience in their area of interest through direct contact with established scientists and collaboration with their peers.

The pipeline—Undergraduate Student Research Awards At the undergraduate level, NSERC funds student research through the Undergraduate Student Research Awards (USRA) program. In the mathematical and statistical sciences, this is a crucial component of our pipeline, providing an opportunity to interest bright and talented young men and women in pursuing research in mathematics and statistics. Approximately 100 undergraduate students from mathematics and statistics departments benefit from this program each year. Undergraduate research has a very significant impact on subsequent graduate training: many of our leading research mathematicians and statisticians started their research careers in NSERC's USRA program. The students are also a crucial component of research programs for professors at universities that have limited opportunities to attract doctoral students; some departments do not have doctoral programs, and other departments may have fairly small programs in selected areas.

Graduate research training Graduate student research is supported by NSERC through its post-graduate scholarships and Discovery Grants programs. The bulk of individual researchers' Discovery Grants are targeted to the training of HQP. It is a long-standing tradition in the mathematical and statistical sciences to leverage Discovery Grant funding by creating student support packages with

a substantial component of pay for teaching assistants and stipend lecturers. Student support may also include university scholarships, and some graduate students have partial support from collaborative grants and from arrangements with researchers and groups in other scientific fields. In 2011, NSERC provided 60 doctoral-level awards and 56 master's-level awards in mathematics and statistics. The CMS and the SSC reported enrolments in master's and doctoral programs at more than 10 times this number, so financial support from Discovery Grants and leveraged funds is clearly essential.

Post-doctoral training Post-doctoral training is standard in mathematics, and is becoming increasingly important in statistics. NSERC's post-doctoral fellowship program awarded 12 fellowships in the mathematical and statistical sciences in 2011. Most funding for post-doctoral fellows comes from the three mathematical sciences institutes: Fields, CRM and PIMS. In the same year, the institutes provided at least partial support for approximately 70 post-doctoral fellows, the majority in fields related to thematic programs or collaborative research groups.

Collaborative research The opportunity to gain experience in collaborative research is increasingly important in the mathematical and statistical sciences. In industrial mathematics and statistics, the Mprime Network of Centres of Excellence (NCE) has been an important source of research opportunities for training HQP. The projects supported by Mprime, until recently, offered students both the opportunity and funding to work on research projects in settings outside academia. They also provided students the chance to gain experience working in research teams on challenging problems in five theme areas: Biomedical and Health; Environment and Natural Resources; Information Processing; Risk and Finance; and Communication, Networks and Security. Funding from the NCE was matched by industry contributions (see Chapter 6 for more details). Similarly, the National Program for Complex Data Structures (NPCDS) seeded collaborations that placed statistics students in scientific laboratories so they could learn the language of the collaborative discipline along with their statistical training.

This LRP includes several suggestions to build on these initiatives as a springboard to future progress on training for collaborative research and industrial

The Fields-Mitacs Summer Undergraduate Research Program hosts about 25 gifted undergraduates annually from Canada and around the world to work in research teams with supervisors from thematic programs and partner universities. The program recruits outstanding graduate students to Canadian universities.

"… after I spent two months at Fields visiting seminars, lectures, and talking to professors and students, I realized that, for me, Toronto is the best place to do a PhD."

Lucy Kadets, University of Toronto graduate student from Kharkiv, Ukraine

innovation. The Mprime proposals outlined in Chapter 6 will build on past experience—and Mprime's many industrial connections—to expand opportunities for students to develop research collaborations in industry and government. The mission of the NPCDS will also be continued with the newly developing Canadian Statistical Sciences Institute, discussed in Chapter 5.

The three mathematical sciences institutes—along with the Atlantic Association for Research in the Mathematical Sciences (AARMS), Mprime and the Banff International Research Station (BIRS)—have provided infrastructure and financial support for summer schools that enable graduate students to collaborate with leading international researchers on advanced research topics. Mathematical modeling camps and industrial problem solving workshops introduce students to Canadian industry, and broaden their views on the applicability of their quantitative training. Our community members are also actively developing programs through the universities, mathematical institutes and Mprime to build students' so-called "soft skills"—communication, team building, leadership and project management are all essential components of collaborative research. Post-doctoral fellowships are essential training for students who are deeply involved in collaborative research, and training in soft skills is an important aspect of the post-doctoral experience.

Leveraging of the NSERC investment in the mathematical sciences institutes with provincial and university funds has enabled an expansion of support for post-doctoral fellows. For statistics and applied mathematics, the Mprime NCE is an important source of funding and research opportunities for students in applied and industrial mathematics. Similarly, the leveraging of the NSERC investment in BIRS with international and provincial funding provides opportunities for intensive research workshops in fields of current scientific importance. There is also some research funding available as an adjunct to the Canada Research Chairs program, and depending on the region, there may be some funding programs, often for early-career researchers, through university and provincial competitions.

Collaboration and Training

The Institut des sciences mathématiques (ISM) coordinates advanced master's and doctoral-level courses throughout Quebec, and introduces promising undergraduates to mathematical research. Working closely with CRM, ISM arranges for post-doctoral fellows to supervise undergraduate summer research projects—a special training opportunity for both groups.

The Pacific Institute for the Mathematical Sciences (PIMS) International Graduate Training Centre in Mathematical Biology has recruited 36 students to the PIMS universities since 2008. The centre organizes research opportunities, workshops and videoconferences, and offers online courses to all the PIMS partner universities.

The Role of Discovery Grants

The importance of NSERC's Discovery Grants program to mathematical and statistical research in Canada cannot be overstated. For almost all researchers in these fields, Discovery Grants are the fuel that drives their research careers and enables their science to advance at international levels. In several sub-disciplines of mathematics and statistics, Discovery Grants are the only available source of stable funding (see Table 3.1 for an overview of Discovery Grant funding for mathematics and statistics).

Discovery Grants are awarded competitively, following a rigorous system of peer review. Grants are awarded for a program of research, and permit flexibility in problems tackled and methods used, as is appropriate for investigator-driven explorations. As mentioned earlier, Discovery Grant funding is largely used by researchers to support undergraduate research projects, graduate student research and post-doctoral fellows. Other uses of the funding include travel for collaborations and research exchanges at workshops, conferences and international symposia.

Discovery Grants are Canada's unique national resource for basic research in the natural sciences and engineering—permitting researchers the freedom to explore in unexpected directions, and providing students with the opportunity to strengthen their foundation in basic research. For researchers with other sources of research funding, a Discovery Grant provides the core funding on which allied research efforts can build. For those without other sources of research funding, obtaining a Discovery Grant is key to their ability to train graduate students and to participate in the global research community.

Table 3.1 Discovery Grants Expenditures
Proportion of Discovery Grants and Discovery Grants funding held by Mathematics and Statistics

Year	DG Funds for Math / Stats ($Millions)	Total DG Funds ($Millions)	% Funds for Math / Stats	Number of Grants for Math / Stats	Total Number of Discovery Grants	% Grants for Math / Stats
2006–2007	16.77	323.65	5.2%	984	10,009	9.8%
2007–2008	16.83	326.05	5.2%	985	10,251	9.6%
2008–2009	17.16	323.69	5.3%	989	10,340	9.6%
2009–2010	17.32	330.50	5.2%	959	10,200	9.4%
2010–2011	17.12	327.96	5.2%	917	9,903	9.3%
2011–2012	16.73	330.27	5.1%	912	9,862	9.2%

Source: Data extracted from published competition results, 2007–2012 (NSERC, 2012a)

Opportunities and Challenges

Canadian investment in the mathematical and statistical sciences is both essential and cost-effective. By supporting basic research in abstract mathematics and the foundations of statistics, platforms are built for innovation in the future. Moreover, the current explosion of activity in applied and applicable mathematics puts Canada at the forefront of research in important societal contexts. The demand for statistical expertise in understanding vast quantities of data and complex phenomena from a robust quantitative perspective is essentially unbounded. The strength of Canada's mathematical and statistical sciences communities in these and other areas makes investment in the mathematical and statistical sciences an outstanding opportunity for Canada to advance discovery and innovation.

The resources needed to build on our successes are not large, yet the potential for positive impact is significant across all areas of Canada's scientific enterprise, the economy and society. The growing demand for quantitative training magnifies the impact of the mathematical and statistical training of students for the knowledge economy—either for careers in industry, government or academia. Research findings from the mathematical and statistical sciences are essential to fuel scientific discovery and commercial and societal innovation of all kinds.

The phenomenal success of the mathematical and statistical sciences communities in leveraging Discovery Grants with funding from other sources also enhances the value of almost any investment in mathematics and statistics. Our researchers extend the impact of their NSERC funding through a diversity of international research collaborations, programs at the mathematical sciences institutes, and interdisciplinary and industrial collaborations that touch on almost every aspect of science, innovation and society. Strengthened funding for mathematics and statistics researchers—from NSERC or other sources—will almost certainly act as a powerful accelerator of discovery and innovation.

Table 3.2 Discovery Grant Award Values for Mathematics and Statistics 2012

Bin	% of Awards (approx.)	Value of Award ($)
A	3%	60,000
B		53,000
C		45,000
D	1%	40,000
E	3%	35,000
F	6%	30,000
G	7%	25,000
H	9%	21,000
I	9%	15,000
J	22%	12,000

In 2012, the dollar amounts of grants were assigned according to the bin levels shown here. Approximately 40% of successful grantees have grants of $21,000 or less.

Source: Constructed from NSERC's published Discovery Grants Competition Results (NSERC, 2012a)

Discovery Grants Given the critical role played by Discovery Grants in supporting mathematical and statistical research in Canada, discussion of the issues relating to the Discovery Grants program—and the evaluation system in particular—figured prominently in all of our community consultations.

- **Level of funding** Among the issues raised, the level of Discovery Grant funding in mathematics and statistics emerged as one of our communities' most serious concerns. This matter touches on Canada's research enterprise—and on our vision for international excellence and the ability to contribute solutions to global challenges—in several ways. These include:
  - ***Building HQP*** With 70 per cent of researchers receiving less than $20,000 per year in funding, the majority can at best provide full research support for a single student (see Table 3.2). Even our researchers receiving the highest grant levels do not have sufficient funds to completely support a single post-doctoral fellow each year.
  - ***Grant size*** Average grant size in mathematics and statistics is the lowest among the NSERC disciplines, largely for historical reasons (see Table 3.3).[5] While the quality of the incoming applicants has continued to increase, NSERC Discovery Grant funding has been essentially constant, and this has put tremendous pressure on each and every Discovery Grant proposal. This is not unique to the mathematical and statistical sciences; the pressure on the Discovery Grants program from all disciplines continues to increase. However, the large imbalance of the average grant sizes for mathematics and statistics relative to other disciplines is inconsistent with comparisons of costs of research and expansion of training programs. Highly rated researchers in the Mathematics and Statistics Evaluation Group have routinely submitted ambitious and realizable proposals that could support at least twice as much training and research collaboration as is actually funded. With the increased emphasis on training in the evaluation of Discovery Grants, and the decreased emphasis on historical funding levels for individual investigators, there are strong arguments for ensuring that grant levels across disciplines are consistent with the need for funds for training.

Supporting HQP—Community Feedback

"My grant was just renewed at $30K. Let's say that I supervise one student at $10K per year —that leaves me $20K for post-docs. To make a two-year offer at $50K per year, which in our department we have found is the minimum needed to be competitive, I need four years' worth of grant money. This assumes that I will travel to only one conference per year, and that the student and the post-doc don't travel at all…"

  - ***Single envelope*** Many in our communities were also concerned that having Discovery Grants and the mathematical sciences institutes funded from a single envelope could further erode the level of Discovery Grant funding. These concerns can be allayed by setting a fixed boundary between the two types of funding at least for the first five years, while we gain experience with the envelope model.

5 It may once have been the case that mathematics and statistics researchers had no need for equipment, and tended to work intensively with very few students at one time. However, this model no longer reflects the modern enterprise of mathematical and statistical sciences research, where collaboration is increasingly common and access to high-performance computing is necessary to handle large data sets.

Table 3.3 Discovery Grants 2009–2012
Success Rates and Average Grant Sizes in the Mathematics and Statistics Evaluation Group

Year	Average Grant		Success Rate	
	Math / Stats ($)	All Fields	Math / Stats	All Fields
2009–2010	19,520	35,388	61.9%	58.1%
2010–2011	16,816	33,691	66.1%	57.7%
2011–2012	20,942	31,270	61.3%	62.2%

Source: *NSERC: Facts and Figures*. Includes Sub-atomic Physics Evaluation Group, and supplements for early career researchers (NSERC, 2012b)

- **Maintaining the pipeline** A critical challenge in ensuring the continued strength and development of the Canadian research community in the mathematical and statistical sciences lies in the need to support undergraduate- and master's-level research, particularly in smaller universities that are isolated from the major centres. Indeed, the current funding system for the Discovery Grants program makes it very difficult for researchers based at smaller universities to obtain the funding that is needed for the training of undergraduate and master's students who will move on to larger universities for their doctoral and post-doctoral work. This is a missed opportunity to tap into a pool of talent. Small institutions, by their very nature, are uniquely positioned to offer a dedicated learning experience and research environment. This position can be further enhanced by the creation of effective scientific networks that are both regional and national in scope.

  Being a department's only expert in a subfield—or one of a very few—may lead to a degree of isolation for some researchers. This can occur at large as well as at small universities. These researchers are not necessarily isolated within the global research community, however it can make it more difficult to have an established student recruitment pipeline. It can also make it very difficult to pool resources to create attractive funding packages for outstanding doctoral or post-doctoral prospects. Concern was expressed to the LRP Steering Committee that isolation in a research area, or a location, may impact women more than men.

Encouraging diversity The mathematical and statistical sciences communities continue to struggle with diverse representation at the graduate and post-doctoral student and professorial levels, particularly for women and certain ethnic groups. Extensive studies across North America suggest a number of factors contribute to the problem:

- Relatively smaller enrollments in honours programs
- Lack of encouragement to pursue mathematical or statistical science
- Unconscious bias in reviewing files
- Absence of role models
- Lack of proactive efforts to recruit and retain diverse candidate pools

The last decade has produced many studies and examples of improvements at all levels, particularly in the United States, where a range of programs have been launched. The Canadian mathematical and statistical communities must access the broadest pool possible to ensure continuing excellence. This will require a combined effort from departments, professional organizations and institutes to better understand and apply best practices for attracting and advancing a diverse array of talent.

Although NSERC's review of its University Faculty Award program for women and minorities concluded that the program did not have a large impact on gender balance, in the mathematical sciences in particular, it did seem to lead to an increase in the number of female appointments. Anecdotal evidence suggests that efforts to recruit women and minorities to faculty positions have been less successful since the program ended.

Supporting interdisciplinary research Research in the mathematical and statistical sciences is often inherently interdisciplinary in nature. For this reason, the LRP Steering Committee is concerned that barriers to funding interdisciplinary research seem to persist—and may even have increased—after the restructuring of the Discovery Grant Evaluation Groups in 2009. This impression stems partially from the fact that the number of reviewers on proposals has decreased to five researchers, some of whom may be selected for their expertise in one component of the proposal and may not themselves have interdisciplinary research programs. Most successful research proposals are "championed" by one or more reviewers or external referees, and it may be difficult to find such champions for proposals that cross several discipline boundaries.

Similar concerns have been raised by statisticians in applied areas. The problem is particularly acute in biostatistics, where research programs can fall not only between the cracks of two Evaluation Groups at NSERC, but between the mandates of NSERC and the Canadian Institutes of Health Research (CIHR). Other research programs cross into the domain of the Social Sciences and Humanities Research Council (SSHRC). Research in actuarial science and mathematical finance, in particular, may overlap with demography, mathematical economics, management sciences, accounting and psychology—all areas supported by SSHRC—and with the NSERC fields of operations research and engineering.

The LRP Steering Committee is also concerned that the present imbalance of funding between Evaluation Groups gives researchers in some subfields a strong incentive to tailor their research programs to other Evaluation Groups. In some cases, this may be appropriate to the evolution of the research program, but it may also create an artificial division between theoretical and applied research, to the detriment of both.

One possible solution for handling interdisciplinary research is to create a mechanism to share the funding across more than one Evaluation Group; this should help prevent artificial inequalities and strengthen the research proposal.

A better solution is a new budgetary model with funding assigned to Evaluation Groups based on costs of research, rather than historical norms.

Undergraduate Student Research Assistantships The LRP Steering Committee heard from many researchers, particularly in smaller universities, about the need for improved flexibility around the Undergraduate Student Research Assistantship (USRA).

Undergraduate research is important for the new knowledge it generates, and for the unique type of training that it provides. It is an essential driver of the pipeline for Canada's research effort in the mathematical and statistical sciences. Many universities with limited doctoral programs, or even limited master's programs, have been successfully priming this pipeline for years. Students who go on to advanced research have a "head start" on their understanding of how to do research. Students who use their training in the job market have experience in tackling problems that are sometimes not well defined, that have not been solved, and that require thinking from several different points of view.

As a rule, supervisors of USRA grants are required to hold a current NSERC grant, although exceptions can be made upon special application. A mechanism by which qualified researchers have the opportunity to apply for USRA supervision, without necessarily holding current NSERC funding, would increase research diversity and strengthen our research pipeline.

Team Grants Team Grants provide another mechanism for strengthening research diversity. However, these grants are at present underutilized. Some reasons for this seem to be a lack of visibility, an emphasis in departments on individual grants for tenure and promotion evaluation, and a lack of clarity in the review system. A mechanism for funding Team Grants for partnerships where researchers have different funding needs would enable increased diversity across the mathematical and statistical sciences research effort. For example, a Team Grant that brings together researchers at institutions with doctoral programs with researchers at primarily undergraduate institutions could make important contributions to our pipeline. While the funding needs of the researchers might be quite different, the opportunities for skills and knowledge transfer through collaboration could provide a rich environment that supports research and training at all levels.

International Comparisons

Canada is in global competition for the best researchers and must offer a world-class research environment if it is to attract and maintain researchers who can achieve international leadership in discovery and innovation. Without adequate funding, we are in danger of losing some of our best researchers to other countries.

Competition from mathematics powerhouses such as the US and France is particularly fierce, with both countries consistently increasing their level of support for research in the mathematical sciences. While NSERC is the only source of funding for basic research in Canada, the US has several additional programs for funding basic research to complement those of the National Science Foundation (NSF). Since 2007, the NSF allocation for research support in the mathematical and statistical sciences through the Division of Mathematical Sciences (DMS) has increased yearly by 2.9 per cent, 6.2 per cent, 7.4 per cent and 5 per cent, to reach $US 241 million. This followed a period of doubling of the DMS budget in the early 2000s. The National Institutes of Health (NIH) in the US also provides significant funding for methodological research in the statistical sciences.

The news from France is even more dramatic: the Centre national de la recherche scientifique (CNRS) has announced that the budget for mathematics within CNRS will be doubled, and that a national institute will be created with a mandate to support the mathematical sciences within the CNRS.

It should also be noted that emerging powers such as China, Singapore and Korea are making enormous investments for the promotion of mathematical and statistical sciences research. Korea will host the International Congress of Mathematicians in 2014, and has already established two major mathematical sciences institutes, with the explicit goal of helping Korea become one of the major centres for mathematical and statistical sciences research in the world.

Going Forward

Flexibility and diversity are essential for successful research investment in the mathematical and statistical sciences. Research advances and training of the next generation of researchers require broad support. We know that the mathematical and statistical sciences will be needed in our efforts to tackle society's most pressing problems, but it is difficult to predict in advance which particular techniques or research areas will be needed.

As we move forward, it will be important to ensure that large institutions have adequate resources for the training of graduate students and post-doctoral fellows *and* that small institutions have the resources to maintain research programs for faculty and students. In the recommendations below, we emphasize measures that support training in research methods and techniques; in Chapter 6 we also outline a proposal for training in the skills required for collaboration.

Recommendations

These recommendations are considered by the LRP Steering Committee to be the most pressing issues affecting Discovery Grants and funding for basic research and training. A detailed list of all the report recommendations is provided in Chapter 8, where we have added some recommendations more focused on process.

- **Funding levels** NSERC should invest in Canada's mathematical and statistical sciences research via Discovery Grant levels that reflect the importance of the research base to Canada, and that acknowledge that the costs of research are similar to those in several related science and engineering disciplines. For example, computer science, operations research and theoretical sub-disciplines for several areas of science and engineering would be reasonable groups for comparison. This needs to take into account funding of HQP, potential supervision capacity, success rates and distributions, and international trends in supporting the mathematical and statistical sciences.
- **Percentage of total funding** Under a scenario of stable funding, the new Mathematics and Statistics envelope should have a fixed percentage of its funds allocated for support of Discovery Grants. We recommend that this amount be 81 per cent for the next five-year cycle, based on a total annual Discovery Portfolio envelope for mathematics and statistics of $21 million.
- **Undergraduate Student Research Awards** The LRP Implementation Committee should work with NSERC to develop more flexible rules around Undergraduate Student Research Awards (USRAs). In particular, mechanisms are needed to qualify a USRA-supervising professor without the requirement that he or she hold a current NSERC award.
- **Team Grants** The LRP Implementation Committee should work with NSERC on creating more flexible rules for Team Grants. These rules could include a range of initiatives to increase support for small institutions, interdisciplinary proposals and pipeline programs.
- **Process** The LRP Implementation Committee should work with NSERC to increase flexibility in programs and process, as detailed in Chapter 8.

CHAPTER 4

Research and Discovery—Thematic and Collaborative Resources

Overview

Canada is home to three international mathematical sciences institutes: the Centre de recherches mathématiques (CRM), the Fields Institute for Research in Mathematical Sciences (Fields) and the Pacific Institute for the Mathematical Sciences (PIMS). The new Canadian Statistical Sciences Institute (CANSSI) is in development. Canada also hosts the Banff International Research Station for Mathematical Innovation and Discovery (BIRS).

Each of the mathematical sciences institutes and BIRS have programs that are global in scientific scope, impact and participation, but also fill important national needs by fostering interdisciplinary collaboration and building links with Canadian industry for innovation. Their flagship thematic programs and workshops create opportunities for groundbreaking research and provide important training grounds for early-career researchers and students from Canada and abroad. The newly proposed CANSSI aims to become an equal partner in the national system of mathematical and statistical sciences institutes.

Together—and individually—these thematic and collaborative resources are key supports for our communities' vision: for Canada to be a world leader in the mathematical and statistical sciences, and to be a driving force in interdisciplinary research and innovation that contributes solutions to important Canadian and global challenges.

Research institutes are now established assets for the mathematical and statistical communities around the world. The worldwide growth of institutes has transformed mathematical and statistical sciences research in almost every corner of the globe. The capacity to bring the world's leading researchers and a large number of beginning scholars in an area together for a sustained period of knowledge exchange and collaboration has fostered global research networks, rapid progress on some of the most challenging problems, and new interdisciplinary research. It would not be an exaggeration to say that a large majority of the top-level mathematicians in the world under age 50 have spent time at a mathematics institute at key formative periods in their careers. In Canada, practically every active researcher in the mathematical and statistical sciences has benefited from institute activities.

The mathematical sciences institutes and BIRS have brought great global visibility to the mathematical sciences in Canada, and have brought distinguished

International Mathematical Sciences Institutes—Transforming Science

- Global research networks
- Rapid progress on grand challenges and pressing problems
- Interdisciplinary research
- Innovative training approaches for Highly Qualified Personnel (HQP)
- Leadership in education, industrial linkages and public outreach

Canada's thematic and collaborative resources—CRM, Fields, PIMS and BIRS—are global in scientific scope, impact and participation while meeting important national needs.

Canada's Mathematical Sciences Institutes—Key Resources for HQP

The institutes and BIRS provide unique opportunities for students and early-career researchers to work and learn from some of the best in the world.

- Post-doctoral fellows
- Summer schools
- Research summits
- Graduate courses
- Undergraduate and graduate conferences

A Unique Lens on Mathematical Research

Canada's mathematical sciences institutes offer distinctive features that increase their global and national impact.

- CRM's research networks link 250 senior researchers into 10 research laboratories, each with an extensive worldwide network. This approach builds remarkable synergies and has led to the world's first unified doctoral school in mathematics.
- Fields' incubated companies, both commercial and non-profit, are unique among mathematical sciences institutes worldwide. Success stories include JUMP, R^2 Financial Technologies (recently acquired by McGraw-Hill) and QWeMA (Quantitative Wealth Management Analytics Group).
- PIMS' Collaborative Research Groups (CRGs) provide resources over a two- to three-year period to groups of researchers at PIMS sites. These opportunities enable intense research concentration, international collaboration and enhanced post-doctoral training.

international scientists to Canada on a scale that universities alone cannot achieve. They have been key factors in the recruitment of some of our country's leading mathematical scientists and rising young researchers. In *The State of Science and Technology in Canada, 2012* report (Council of Canadian Academies, 2012), 66 per cent of internationally top-cited researchers in mathematics and statistics affirmed the statement "Does Canada have world-leading research programs or infrastructure of worldwide importance?"

These four institutions currently receive NSERC funding through the Major Resources Support (MRS) program, at a total level of approximately $4.1 million per year. At the same time, they use NSERC support to very effectively leverage provincial, international and university funding, and their activities provide great added value to Canada's universities and provinces. As we detail later in this chapter under Funding Thematic and Collaborative Resources, the institutes and BIRS are unique among mathematical sciences research institutions worldwide in the proportion of their funding that is leveraged by national research grants.

The institutes and BIRS will continue to prosper only with the broadest possible support from the Canadian mathematical and statistical sciences communities. Many activities at these institutions arise from ideas developed by the community. The leadership at the institutes and BIRS are proactive in stimulating and supporting this process, as well as in advancing the critical role played by mathematics and statistics in the global context. The four institutions are continuously innovating to provide Canada with knowledge, people and entrepreneurial advantages.

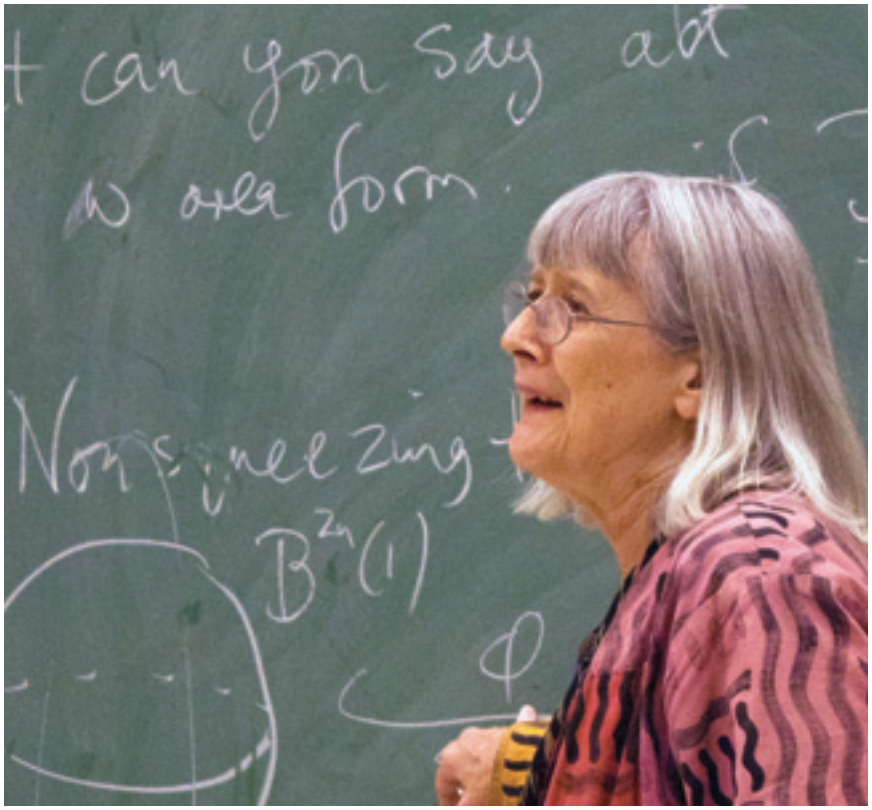
In the following sections, we outline the current landscape for the institutes in Canada, some of the opportunities and challenges faced by these resources, and our communities' plans for the next five to ten years.

The Mathematical Sciences Institutes

Activities of the mathematical sciences institutes span a wide range of programs and formats at all levels of research, education and training of HQP. These include thematic programs of two months to one year in length, collaborative research groups, workshops and conferences, graduate courses for university credit, summer schools, seminar series, and distinguished and public lectures. The institutes have large and diverse post-doctoral programs as well as vibrant educational and outreach activities. They also have long-running programs in collaboration with commerce and industry.

The institutes have developed structures that reflect the fundamental role of the mathematical sciences in other areas of scientific research. Examples include the CRM laboratories on Brain Imaging (PhysNum) and on Quantum Information (INTRIQ), Fields' Centre for Mathematics and Medicine (CMM) and its Professional Risk Managers' International Association (PRMIA) and Quantitative Finance Seminars, and PIMS' International Graduate Training Centre

(IGTC) in Mathematical Biology and Math Modeling in Industry organized in partnership with the Institute for Mathematics and its Applications in Minnesota. All of the mathematical sciences institutes offer Industrial Problem Solving Workshops, and the 2013 Mathematics of Planet Earth initiative—begun by the CRM, Fields and PIMS—has grown to involve collaboration with more than a dozen institutes around the world.



Background The CRM is Canada's oldest international institute in the mathematical sciences. Established in 1968 at the Université de Montréal, it now partners with seven major universities in Quebec and Ontario, and has formal links with many institutes and universities in Europe, the US and Asia.

The Fields Institute was founded at the University of Waterloo in 1991, and has, since 1995, occupied a building on the University of Toronto campus designed for scientific communication. Fields partners with seven principal sponsoring universities in Ontario and 17 affiliates in Canada, the US and Europe.

PIMS was created as a distributed institute in 1996 by the mathematical sciences community in Alberta and British Columbia, and was subsequently extended to Washington State and Saskatchewan. The PIMS consortium has eight member universities in Western Canada and Washington State, and 14 affiliated institutions. In 2012, PIMS' headquarters moved to a new sciences building on the University of British Columbia campus.

With up to 3000 registered participants in the programs of each of the three mathematical sciences institutes annually, the institutes organize an enormous spectrum of activities throughout Canada for researchers, university professors, teachers, post-doctoral fellows and students (beginning with Kindergarten to Grade 12), as well as for users of the mathematical sciences in commerce and industry.

People As mentioned in Chapter 3, scientific research and discovery begins with people, and the development of their skills and expertise. Canada's mathematical sciences institutes create unique opportunities for training graduate students and post-doctoral fellows on a scale that universities alone cannot provide: opportunities to work with the best in the world, programs with other disciplines and commercial / industrial partners, research collaborations with young international colleagues, and joint supervision of research by Canadian and international scientists.

Reflecting the Breadth of the Mathematical Sciences

Thousands of scholars take part in institute programs each year; about half of these are international participants. These programs cover the breadth of the mathematical sciences.

- Pure and applied mathematics
- Probability and statistics
- Computer science
- Collaboration between the mathematical sciences and engineering, physical, biological and social sciences
- Interface with areas as varied as medicine, economics and finance, telecommunications, information systems, public health, climate and the environment.

Mathematical and Statistical Sciences Institutes Around the World

Canada's mathematical sciences institutes enjoy the highest level of international visibility and prestige. They rank among the elite mathematical sciences institutes in the world:

United States

- Institute for Advanced Study (IAS)
- Mathematical Sciences Research Institute (MSRI)
- Institute for Mathematics and its Applications (IMA)
- Institute for Pure and Applied Mathematics (IPAM)
- Statistical and Applied Mathematical Sciences Institute (SAMSI)
- Mathematical Biosciences Institute (MBI)
- Institute for Computational and Experimental Research in Mathematics (ICERM)

United Kingdom

- Isaac Newton Institute for Mathematical Sciences (Newton)
- International Centre of Mathematical Sciences (ICMS)

France

- Institut des Hautes Études Scientifiques (IHES)
- Institut national des sciences mathématiques et de leurs interactions (INSMI)

Germany

- Max Planck Institute for Mathematics (MPIM)
- Mathematical Research Institute of Oberwolfach

Brazil

- Instituto Nacional de Matematica Pura e Aplicada (IMPA)

Japan

- Research Institute for Mathematical Sciences (RIMS)

Norway

- (sfi)^2 Statistics for Innovation

The three mathematical sciences institutes provide complete or partial support for 70 to 75 post-doctoral fellows in a given academic year. Indeed the institutes are the primary source of funding of this important aspect of training of HQP and the next generation of mathematics talent in Canada. This is an invaluable enhancement of NSERC's post-doctoral fellowship program, which awarded 12 fellowships in mathematics and statistics in 2011.

The institutes provide unique contemporary vehicles for research training of students. At the graduate level, courses for university credit are taught at all three institutes by top international researchers as part of thematic activities. In addition, the Séminaire de mathématiques supérieures—a prestigious summer school celebrating its 50th anniversary this year—is held at CRM, and is now supported by all three institutes as well as the Mathematical Sciences Research Institute (MSRI) in Berkeley. As a national initiative, it will take place certain years at Fields and at PIMS. The institutes' summer schools, often held at partner universities, are critical to advancing areas of research whose expertise is scattered across Canada, and provide superb opportunities for students in these areas to collaborate and discuss their research with global leaders.

The Institut des sciences mathématiques du Québec (ISM), the educational arm of CRM founded in 1991, includes a unified doctoral school that gathers all doctoral programs in mathematics in universities in Quebec and takes full advantage of the graduate schools at CRM. The joint Fields / University of Toronto Dean's Distinguished Visiting Professorship (begun in 2009) has already brought Yum-Tong Siu (Harvard), Nizar Touzi (École Polytechnique) and Artur Avila (Instituto Nacional de Matemática Pura e Aplicada (IMPA and Paris VI) to Toronto to give full-term graduate courses. PIMS' IGTC in Mathematical Biology (begun in 2007) organizes research summits, graduate student interchanges, international training events and career development opportunities, thus providing crucial support for HQP training in an important interdisciplinary area.

At the undergraduate level, the institutes sponsor a joint Canadian Undergraduate Mathematics Conference (CUMC). A CRM program administered by ISM brings post-doctoral fellows as supervisors together with undergraduates for summer research projects—a special training opportunity for both post-doctoral fellows and students. Fields has recently introduced the Fields Undergraduate Network (FUN) and the Fields-Mitacs Undergraduate Summer Research Program, bringing top Canadian and international students together for two months of research activity. PIMS hosts undergraduate summer schools at its different sites; in 2012, a summer school in Algebraic Graph Theory was held at PIMS Simon Fraser University.

Developing community The mathematical institutes leverage university and regional partnerships in many important ways. They have been

key factors in the recruitment of some of Canada's leading mathematical scientists, with a particular role in the success of the Canada Research Chairs program. Many young researchers trained as post-doctoral fellows at the institutes have taken faculty positions at Canadian universities.

The institutes also foster excellence in research at smaller universities by providing for participation of their students and faculty in institute activities and by using the prestige of their research programs to attract internationally renowned researchers to partner universities. Visiting institute researchers who collaborate with partner universities often interact with students, contributing to a distributed training model that is important to mathematics in Canada.

The mathematical sciences institutes and BIRS, together with Mprime, have served as the primary source of conference support in the mathematical sciences throughout Canada, and are committed to providing seed funding for the many events that take place every year. In particular, they provide key support to the meetings of professional societies such as the Canadian Mathematical Society (CMS), the Canadian Applied and Industrial Mathematics Society (CAIMS) and the Statistical Society of Canada (SSC).

Research and discovery Thematic programs are the flagship activities of the mathematical sciences institutes. At both CRM and Fields, thematic programs of between two and six months bring together the world's top players and developing researchers for periods of intense communication and collaboration. Thematic activities at PIMS are organized through Collaborative Research Groups (CRGs). These are two- to three-year programs of intense focus at PIMS member universities that create enduring research collaborations among Canadian scientists and their international colleagues.

Some institute programs have literally launched new scientific disciplines that have achieved high international visibility. The CRM Thematic Program on Additive Combinatorics in 2005–2006 featured Terence Tao as the *André-Aisenstadt Lecturer.* A few months later, Tao was awarded the top international honour in mathematics: the Fields Medal. The Fields Institute's 1997 programs on Model Theory and Geometry and Singularity Theory essentially created the area of *O-minimal geometry.* This led to the surprising success of model-theoretic methods in geometry, dynamics and complex analysis, as well as geometry-inspired advances in model theory. PIMS' CRG in Probability was the catalyst behind a series of highly successful international PIMS Probability summer schools that are now held every other year.

The institutes' programs also create networks that cross traditional disciplinary boundaries. For example, in 2009, the CRM hosted a program on Brain and Molecular Imaging that created linkages with the Hôpital La Salpêtrière in Paris and the Institut de universitaire gériatrie de Montréal. The 2012 Fields program on Inverse Problems and Imaging—held partly in collaboration with Mprime—spans activity from pure harmonic analysis to a focused Industrial Problem Solving Workshop and a Summer Program on the Mathematics of Medical Imaging organized in collaboration with Ontario hospitals.

Inspiring Excellence

The three mathematical sciences institutes award prizes for excellence in research that are an inspiration to ambitious young scientists.

The joint *CRM-Fields-PIMS Prize*
Canada's most prestigious prize in mathematics

The CRM *Aisenstadt Prize*
for young mathematical scientists

The joint *CRM-SSC Prize in Statistics*
for mid-career scientists

The joint *CAP-CRM Prize in Theoretical and Mathematical Physics*
for theoretical mathematicians

The joint *CAIMS-PIMS Early Career Award in Applied Mathematics*

The Mprime / CAIMS *Industrial Mathematics Prize*
for exceptional research in industrial mathematics

International Leadership and Visibility

Canada's mathematical sciences institutes play a role in practically every significant international initiative involving peer institutions.

At the General Assembly of the International Mathematical Union (IMU) in Bangalore (2010), the Fields Institute presented one of three highly competitive bids to host the permanent headquarters of the IMU. The initiative brought IMU endorsement of the Fields Medal Symposium—to begin at the Fields Institute in October 2012—celebrating the achievements of recent Fields Medalists. The symposium has private sponsorship. It will be one of the highest profile events in the global mathematics community, and will highlight the Canadian origins of the Fields Medal.

AARMS Summer School—Building International Connections in Atlantic Canada

The AARMS graduate summer school invites highly regarded faculty and graduate students from around the world to Atlantic Canada for a four-week program in the mathematical sciences and their applications. The multicultural and international flavour of the summer school is one of its strengths—enabling students from the region to form lasting connections with their peers and established mathematicians from all parts of Canada and the globe. In 2013, the AARMS summer school will focus on the international theme of *The Mathematics of Planet Earth.*

Reflecting the fundamental role of the mathematical and statistical sciences in other areas of scientific research, the institutes sponsor many activities in allied fields such as computer science, theoretical physics and geophysics. Many thematic activities over the last decade have reflected the institutes' support of exciting new developments in other areas that need mathematical tools to advance. Examples include the following: CRM Programs in Stochastic and Multiscale Modeling (2004) and Quantum Information (2011); Fields' programs in Foundations of Computational Mathematics (2009), Quantitative Finance: Foundations and Applications (2010) and Mathematics of Drug Resistance in Infectious Diseases (2010); and PIMS Collaborative Research Groups in Mathematics of Quantum Information (2010–2013), Applied and Computational Harmonic Analysis (2011–2014) and Optimization: Theory, Algorithms, and Applications (2012–2015).

International cooperation and impact The Canadian institutes are equal partners in the community of North American mathematical sciences institutes, and also have special connections to Asia and Europe. CRM and PIMS are only two of a handful of international institutes to be designated "Unités Mixtes Internationales" of the CNRS (France), and will soon be joined by Fields in this distinction. CRM recently signed an exchange agreement with the two main Tata Institutes in India, and Fields has an exchange agreement with the City University of Hong Kong. PIMS has played a leading role in organizing the Pacific Rim Mathematical Association (PRIMA), with collaborative agreements signed with research institutes in Australia, Chile, China, Japan, Korea and Mexico. Strategic funding from the three institutes enhances international collaborations. An example is their support for the Canada-France and Canada-Mexico meetings in mathematics and statistics.

Innovation and connections The Canadian mathematical sciences institutes are highly innovative in expanding opportunities to advance the mathematical sciences in Canada. In 1997, they jointly founded Mitacs, a remarkably successful Network of Centres of Excellence (NCE), which has made far-reaching contributions to Canada's innovation strategy by building partnerships between academics and industry. The creation of BIRS in 2003 was a joint effort of PIMS and MSRI in California.

The three institutes jointly provide funding for the Atlantic Association for Research in Mathematics (AARMS), and have done so since 2002. AARMS has successfully leveraged this funding to obtain contributions from partner universities and the provincial governments. Through its program of research workshops and conferences, AARMS has helped researchers in Atlantic Canada develop national and international collaborations. An important element of AARMS is the training it provides for students in the Atlantic region. Each year its four-week international graduate summer school has four advanced courses taught by professors invited from around the world. Since 2007, all of the smaller universities in the region with degree programs in the mathematical sciences have affiliated with AARMS, with Dalhousie, Memorial University and the University of New Brunswick as the principal sponsoring universities. More recently, AARMS has been reaching out to scientists in a wide range of

mathematically intensive disciplines such as theoretical physics, oceanography and other areas of applied mathematics.

From 2002 to 2008, the mathematical sciences institutes worked with the statistical sciences community to establish the National Program for Complex Data Structures (NPCDS). This very successful national initiative was designed to develop interdisciplinary research programs, with leadership from statisticians who would collaborate with scientists seeking to analyze complex data. During its first five years, NPCDS established eight interdisciplinary projects, with partners ranging from government organizations such as Statistics Canada and the Canadian Security Establishment to health research centres such as Cancer Care Ontario. Projects were diverse: forest fire prediction, marine mammal tracking, and climate in agriculture being just a few examples. The success of this program has inspired the proposal for the Canadian Statistical Sciences Institute (see Chapter 5).

To help build Canada's entrepreneurial advantage, the institutes have developed active programs in industrial mathematics, including Fields' Quantitative Finance, Industrial Optimization and Risk Management Seminars, and PIMS' Shell Lunchbox Series in Calgary. Industrial Problem Solving Workshops (IPSWs) are now organized on a rotating basis at all three institutes, with a national committee to coordinate these events and maximize their impact. The CRM launched the RCM^2 network, a consortium of companies and university-based research centres. More specialized activities, bringing together academics, students and industry representatives, have also been organized by the institutes on topics such as inverse problems and the oil industry, and mathematical finance and the health sciences. In 2009, PIMS initiated a collaboration with the Institute for Mathematics and its Application (IMA) in Minneapolis and the Centro de Investigación en Matemáticas (CIMAT) in Mexico to organize Math Modeling in Industry workshops in all three countries on a rotating basis.

Dissemination and outreach All three institutes play a leadership role in sharing the results of their many activities. The CRM publishes a long-standing series of *Monographs, Lecture Notes* and *Proceedings* in collaboration with the American Mathematical Society (AMS) and Springer. The Fields Institute publishes two book series—*Monographs and Communications* (formerly with the AMS and starting in 2012 with Springer)—as well as two peer-reviewed electronic journals—*Mathematics in Industry Case Studies* (MICS) and the new *Fields Mathematics Education Journal*. PIMS has recently introduced *Mathtube,* a Web-based dissemination tool for videos and material connected to PIMS events. The institutes also publish regular newsletters aimed at a general readership. CRM and PIMS publish highly successful outreach magazines for schools—*Accromath* and *PI in the Sky.*

Recognizing that the strength of our HQP pipeline depends crucially on Kindergarten to Grade 12 and undergraduate education, the institutes have developed important educational initiatives aimed at these groups. These include outreach programs like the CRM's highly popular public lectures *Les Grandes conférences,* Fields' *Math Circles, Math Ed Forum* and JUMP, and PIMS'

Mathematics Education—the Research Foundation

JUMP math, founded by educator, Fields Institute Fellow, and prize-winning playwright, John Mighton, OC, is transforming ideas about how mathematics is learned. Mighton *"might well be the nation's mathematical conscience. He not only knows that all children can master genuine mathematics but has repeatedly proved so with his brilliant, no-nonsense… program"*

Andrew Nikiforuk, education writer and award-winning author.

"Teach young people math properly and in the early grades, and they will finish school and become useful contributing members of society… Over the next 10 years, the most sought after university grads will be those with PhDs in math and all types of physics."

Haig Farris, President, Fractal Capital Corporation

Math Mania and *Math Camps*. The institutes have been involved in organizing workshops for teachers, math fairs and contests. PIMS has developed a program to enhance training of Aboriginal / First Nations students and teachers in British Columbia, and also awards the annual PIMS Education Prize. In 2010, PIMS started the Alberta Summer Math Institute in Edmonton, a yearly event for talented high school students from Alberta.

BIRS—A New Level of Scientific Cooperation

Innovative funding partnership
For the very first time, BIRS brought together NSERC, the US National Science Foundation (NSF), Alberta Innovates and Mexico's Consejo Nacional de Ciencia y Tecnología (CONACYT) in an international funding partnership.

International collaboration and exchange
BIRS provides new and exciting opportunities for North American faculty and students, giving them access to their international counterparts at the highest levels and across all mathematical disciplines.

The Banff International Research Station

Inaugurated in 2003, the Banff International Research Station for Mathematical Innovation and Discovery has established, in a few short years, a reputation rivaling that of the famed research centre in Oberwolfach, Germany. BIRS is a North American initiative that addresses the imperatives of collaborative research: cross-disciplinary synergy and intense interactions among scientists. BIRS provides a creative environment for the exchange of ideas, knowledge and methods within the mathematical sciences and their vast array of applications.

The main mode of operation at BIRS is an annual series of 49 weekly workshops, each hosting 42 researchers in disciplines in which the mathematical, computer and statistical sciences are used in deep and novel ways. In addition, the station hosts teams of two-to-four researchers for periods of two weeks to allow collaborative, distraction-free research, or to finish major scientific projects. The setting of the station has also been ideal for summer schools and graduate summer camps, for hosting focused collaborative research groups, and for promoting university-industry interactions. Every year, the station hosts over 2000 researchers from 400 institutions in more than 30 countries who participate in over 70 different programs.

BIRS programs span almost every branch of pure, applied, computational and industrial mathematics, statistics and computer science. This influence also extends to physics, biology and engineering, as well as to economics, finance, psychology and scientific writing. The extraordinary response to the opportunities at BIRS leads to extremely high-quality competitions with almost 170 proposed activities competing for the 49 available weeks. The extensive review and selection process is done by a scientific panel consisting of 30 international experts in the mathematical and statistical sciences as well as in engineering and other applied sciences.

In addition to the five-day workshops and the Research-in-Teams programs, BIRS has hosted NSF's Focused Research Groups, Canada's Collaborative Research Teams, department chairs meetings and other leadership retreats, gatherings for Women in Mathematics, summer schools in emerging areas, student modeling camps, training sessions for Math Olympiad teams, industrial forums, "ateliers" in scientific writing and "Bridges Conferences" for mathematics, music and arts. BIRS has also led the way in hosting workshops that address science and education issues for Aboriginal people.

Funding Thematic and Collaborative Resources

CRM, Fields and PIMS were established with funding from NSERC and from provincial and university partners. NSERC funding of CRM and Fields came originally from the Major Projects Program, which was, at the time, new funding outside the operating grants program. During the period of NSERC's reallocations exercises (1991–2007), the three mathematical sciences institutes were part of the research submissions of the pure and applied mathematics grant selection committees (GSC 337, 336). In the final reallocations exercise, the institutes also submitted a proposal jointly with the statistical sciences (GSC 14) for the National Program on Complex Data Structures (NPCDS). With the termination of the reallocations exercises, the mathematical sciences institutes' funding was moved to the Major Resources Support (MRS) program (itself a revision of the Major Facilities Access program). The most recent proposals, evaluated in 2007 for funding for the five-year period beginning April 2008, were successful in the new MRS program. The current NSERC grants to the mathematical sciences institutes were extended by one year to March 2014, so that applications for further funding will take place after completion of the LRP exercise. This will enable development of a new framework for funding the institutes.

BIRS programs started in 2003, with base funding from the National Science Foundation, NSERC and the Government of Alberta. In 2005, Mexico's CONACYT became a new sponsor. Current NSERC funding of BIRS, through the MRS program, is for the five-year period beginning April 2011.

Each of the institutes and BIRS issues regular calls for proposals for scientific activities. These proposals are evaluated and adjudicated by international scientific committees of renowned mathematical and statistical scientists. This serves then as a double process of peer review, as the proposals for funding have already been carefully evaluated by peer review committees established by NSERC, and in the case of BIRS, by all its funding bodies. There is a very high level of competition for programs funded by the institutes. In addition to the scientific review committees, each institute, and BIRS, has a board of directors that is responsible for overseeing all the operations of each facility.

Making the Innovation Connection

The institutes continue to break new ground in contributing to Canada's innovation agenda. In 1997, they jointly founded the Mitacs Network of Centres of Excellence—a phenomenal success by any measure. In 2011, this NCE assumed the name Mprime Network.

Today, they maintain active programs in industrial mathematics. They are also engaged in finding new ways to extend the impact of Mprime as a knowledge transfer network that advances innovation in Canadian industry, and benefits our economy and society.

Table 4.1 NSERC Funding for Institutes and BIRS
NSERC funding for the mathematical sciences institutes and BIRS is expected to be $4.14 million in 2013–2014

2008–2009	$3,500,000	For PIMS, CRM and Fields
2009–2010	$4,085,000	BIRS award added
2010–2011	$4,085,000	
2011–2012	$4,136,000	BIRS award indexed for inflation
2012–2013	$4,138,000	
2013–2014	$4,141,000	Expected

NSERC funding The annual funding for the three mathematical sciences institutes and BIRS is indicated in the table above. To compare this to the situation in the United States, the NSF funds eight mathematical sciences institutes in the US, as well as three (including BIRS) abroad. The current total annual budget for the eight US institutes is $26 million, or 11 per cent of the NSF budget for the Division of Mathematical Sciences.

NSF allocates another $10 million, 4 per cent of its budget, to conferences and workshops; in Canada, the institutes fund such workshops. An additional $5 million is spent by the NSF on post-doctoral fellowships and about $9 million on Research Training Grants. Thus the total investment by NSF in activities comparable to that of the institutes in Canada is approximately $50 million out of a total budget of $240 million—over 20 per cent of the total NSF budget in the mathematical sciences. In addition, the NSF provides the following annual support for foreign mathematics institutes: BIRS, $684,000; IHES, $253,000; and Oberwolfach, $120,000. The more established institutes in the US, such as MSRI, IMA and SAMSI, each receive about $4.5 million per year. Thus NSERC's total investment in the institutes and BIRS is less than the funding that NSF provides to any one institute in the US.

Leveraging NSERC gets exceptional value for its investment in the mathematical sciences institutes. While individual institutes in Canada are funded at much lower levels at the federal level than in the US, they have all been extremely successful at leveraging this funding. In particular, the total funding of each institute in Canada is comparable to that in the US. The institutes receive major funding from provincial governments and their partner universities, and also receive support from international agencies, commercial and industrial partners, and private contributions. The NSF, for example, is an important contributor to mathematics and statistics in Canada, not only by its direct support of BIRS, but also by grants for support of American participants in institute programs.

Estimates of the total leveraging of direct NSERC funding range from four-to-one, purely on the basis of cash flow, to considerably higher if one includes space, matching post-doctoral and student support, and co-sponsorship of conferences and educational activities. This has created a multiplying effect for NSERC funding, but the latter is still the essential basic funding source on which the institutes must rely to build up their leveraged resources. Base

funding from national government agencies is standard practice for nearly all the mathematical sciences institutes in the world.

Opportunities and Challenges

Building on their strong foundation of research excellence and community collaboration, the institutes are in a position to excel in supporting the many new opportunities that are opening up for the mathematical and statistical sciences —supporting Canada's researchers to advance scientifically while contributing to areas of strategic interest to Canada and the global community.

Some examples of spheres where Canada has the capacity to make a difference in the next 10 years include:

- analysis and structure of data and the digital economy
- quantitative biology and medicine
- energy and sustainability

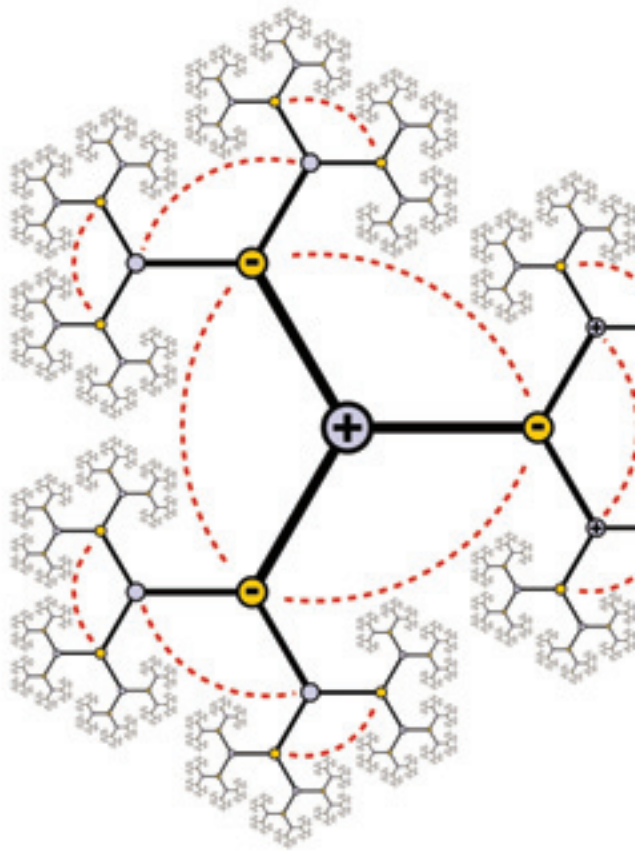
Many of these fields involve increasing interaction between the mathematical and statistical sciences, and in keeping with the vision for this LRP, the mathematical sciences institutes have been working with the statistical sciences community to create the new Canadian Statistical Sciences Institute. Our communities' vision for this new institute is discussed in Chapter 5.

At the same time, fundamental or pure research remains the foundation of scientific creativity and innovation, and will therefore continue to be a strategic priority for the institutes.

Increased collaboration among the institutes within Canada and abroad also represents an important opportunity to heighten our communities' scientific impact. The institutes, and Canadian society, will gain immensely from the enhanced diversity—from geography and size of university partners to gender and minorities—that this collaboration will bring to participation and training in the mathematical and statistical sciences professions.

Examples of collaborative programs already in the works are the Mathematics of Planet Earth initiative (2013), the Fields Thematic Program on Variational Problems in Geometry, Physics and Economics (2014) (part of a one-year program in collaboration with MSRI at Berkeley), and the Industrial Problem Solving Workshops that began rotating among the institutes in 2012.

Over the last year, the LRP Steering Committee received extensive input from the mathematical and statistical sciences communities, including suggestions for institute initiatives and strategies. The following list of challenges includes issues that were raised by the communities:



- **Funding—capacity to respond to growth and change** The NSERC envelope model for funding the mathematical sciences restricts the available funding, at least in the short term, to that now invested in Discovery Grants and the existing thematic and collaborative resources. Over the past five years, this has been roughly stable at $21 million per year. This level of funding does not permit growth in our research infrastructure.
- **NSERC funding model** The envelope model also carries a risk of fixing an artificial boundary between "mathematical and statistical sciences" and "science." This administrative boundary may prove to be ill adapted to interdisciplinary activities of the institutes and their support of a wide range of scientific collaborations in research areas that address the very priorities of Canada's science and technology strategy, including energy, the environment, health and the digital economy.
- **Sunsetting of Mprime** The ending of the very successful Mprime NCE means a loss of $5.4 million in funding for the mathematical and statistical sciences, largely for the support of students. In areas of applied mathematics and statistics, this funding has been essential for helping to supplement the funding from the Discovery Grants program. Of equal concern is the potential loss of the very large network of contacts and collaborators outside of academia. These relationships must be continually renewed and developed, and would be difficult to recover if lost. It is essential that new resources be found to build on this uniquely successful effort. Chapter 6 expands on this point and outlines a vision for a new initiative to maintain the momentum of research excellence and the network of collaborators.
- **Increased collaborative activity in the statistical sciences** The community responses indicated a clear need for institute activity in the statistical sciences to reinvigorate and expand the important scientific collaborations generated by the NPCDS. The LRP Steering Committee responded to this by encouraging the statistical sciences community to discuss opportunities for such activity, and the result is the proposed Canadian Statistical Sciences Institute.

Going Forward

The primary activities of the mathematical sciences institutes and BIRS involve fundamental research and knowledge development. These institutions will continue to advance the mathematical and statistical sciences with the working model that, when exceptional thinkers are brought together in an inspiring environment, transformative ideas will emerge.

A key goal is to continue to develop structures that reflect the unity and universal nature of research in the mathematical and statistical sciences, while maintaining the flexibility to promote significant recent developments, emerging trends and progress at the frontiers of science, and to organize activities related to fast-breaking topics on short notice.

Taking into account the strategic growth opportunities outlined in Chapter 2, the LRP Steering Committee supports several new initiatives for the institutes that are critical to the advancement of the mathematical and statistical sciences in a Canadian and global context, and to the competitive training of Canadian students. These initiatives represent expanding opportunities for people, research and discovery, and innovation and connections—the three pillars of our vision and LRP.

- **Canadian Statistical Sciences Institute** The Committee supports the establishment of the Canadian Statistical Sciences Institute, and the institute directors are committed to working with the statistical sciences community on this initiative.
- **Canadian Network of Mathematical and Statistical Sciences Institutes** The Committee supports the establishment of a Canadian Network of Mathematical and Statistical Sciences Institutes, for increased national coordination of scientific, educational and commercial/industrial programs, with both a global agenda and a national mandate, supported by information and communications technologies. Important joint ventures like AARMS and the rotating Industrial Problem Solving Workshops should be supported and invigorated. CRM, Fields and PIMS plan to coordinate their applications for the next NSERC funding cycle, which begins in April 2014. The institutes will also develop opportunities for increased collaboration on projects of common interest with BIRS, as part of a larger trans-Canadian network.
- **A national innovation strategy for the mathematical and statistical sciences** In light of the termination of NCE funding for the Mprime Network in 2012, a national strategy for continuing engagement of the mathematical sciences community with the country's innovation agenda is an urgent priority. Towards this goal, the Committee supports the efforts of Mprime and the institutes to build a closer relationship with NSERC's Research Partnerships Programs (RPP) Division. More details are provided in Chapter 6.
- **A national electronic network for mathematics and statistics** The Committee supports the development of a common IT platform and a shared interactive electronic network for remote participation in programs of the

institutes, BIRS and Mprime, in particular for courses that are offered for university credit. Increasing use of social media will foster collaboration nationally and internationally, including collaboration with commercial and industrial partners.

- **Collaborative training of graduate students** The Committee supports ongoing development by the institutes of research opportunities for graduate and undergraduate students, with special attention to middle and smaller universities. Institute programs described earlier in this chapter can serve as models. The institutes will further develop collaborative training of graduate students between faculty of different universities, as well as between Canadian faculty and long-term international visitors.
- **Diversity initiatives** The Committee encourages increased participation by women and under-represented groups in all institute activities, on a par with mathematical sciences institutes in the US, where current guidelines aim for 20 per cent participation of women. See Chapter 3 for a discussion of the participation of women in mathematical and statistical sciences research. The institutes will incorporate known best practices to achieve increases in diverse participation. Diversity in training activities is particularly important to the provinces with large numbers of First Nations children and youth.

Recommendations

In scientifically advanced countries throughout the world, institutes are key components of national strategies to maintain excellence and to advance mathematical and statistical research, and their application to science, society and the economy. Thus a global envelope for our community within NSERC must include funding for an institute component.

The recommendations below reflect input from the community and consultation with our international advisory panel. They are presented as well in the set of detailed recommendations in Chapter 8.

- **Percentage of total funding for institutes** Under a scenario of stable funding, the new Mathematics and Statistics envelope should have a fixed percentage of its funds allocated for support of Canada's network of mathematical and statistical sciences institutes and the Banff International Research Station. We recommend that this amount be 19 per cent for the next five-year cycle, based on the current annual budget of about $21 million for Discovery Grants and thematic and collaborative resources. Within this 19 per cent portion, we recommend that the percentage currently allocated to BIRS be reserved for its next competition.
- **Long-term growth** The components of the envelope should have a capacity for long-term growth that reflects opportunities in the mathematical and statistical sciences and their own dynamics. The envelope structure in the long term should be able to reflect the substantial support that the mathematical sciences institutes and BIRS provide to other disciplines. In particular, NSERC should develop mechanisms that would permit partnering of resources between other Evaluation Groups and the Mathematics and Statistics Evaluation Group, in cases where the scientific arguments are compelling.
- **Evaluation and renewal** Clear guidelines for renewal and evaluation of institute activities in the new envelope should be formally established by March 2013, so that evaluations conducted under new guidelines for the envelope can be completed in time to ensure continuity. Performance indicators that are appropriate for evaluating proposals for thematic and collaborative resources should be developed. The tables provided in Appendix B are a first step in that direction. The current NSERC funding cycle for the three mathematical sciences institutes ends on March 31, 2014. A recommended schedule and outline of procedures for the renewal process, modeled on recent competitions, is presented in Appendix B. The current funding cycle for BIRS runs to March 31, 2016. A schedule and outline of the renewal procedure, modeled on recent competitions, is also presented in Appendix B.

CHAPTER 5

Canadian Statistical Sciences Institute

Overview

In 2003, a joint effort between the Canadian statistics community and the mathematical sciences institutes was established with a mission to seed collaborative research projects with statistical leadership. A concerted effort in 2009 to build this National Program on Complex Data Structures (NPCDS) into an institute did not succeed in securing NSERC funding. However, the goal of a national focus for collaboration and development of the statistical sciences remains a high priority of the statistical sciences community.

For this reason, the Statistical Society of Canada (SSC) submission to the LRP Steering Committee called for the formation of a national institute "to support and structure collaborative interdisciplinary research involving the statistical sciences, for the benefit of researchers in all areas of science where massive amounts of data are routinely collected."

Over the course of the development of the LRP, the SSC formed a committee to create a framework for a national institute for statistical science. The committee also worked with the directors of the three mathematical sciences institutes to explore mechanisms for funding. The result is a proposal for the Canadian Statistical Sciences Institute (CANSSI), with a mandate to support national collaborations in both core and interdisciplinary research in the statistical sciences.

This chapter draws on the material in that proposal, and outlines the scientific case for an institute for statistical science and its importance for research and training. Detailed suggestions for governance and operation are provided in the full CANSSI proposal, which was circulated to the statistical sciences community for feedback in April 2012 and endorsed at the SSC Annual Meeting in June 2012.

Background

The NPCDS was funded in 2003 through NSERC's reallocations exercise, with an annual budget of $222,000 per year. The program provided seed funding to researchers to establish scientific collaborations, typically in two stages: an inaugural workshop, followed by a full proposal for an initiative of a two- to three-year duration. Each project received funding for highly qualified personnel (HQP), workshops, travel and dissemination. Research teams were expected to seek additional funding to augment support for these or other activities. Workshops were normally held at one of the mathematical sciences institutes. As the program developed, intensive training schools were also introduced.

NPCDS Projects and Partners

- Statistical Methods for Complex Survey Data (*Statistics Canada, Westat, Workers Safety and Insurance Board* and *Mprime*)
- Canadian Consortium for Statistical Genomics *(Ontario Cancer Centre)*
- Design and Analysis of Computer Experiments for Complex Systems *(Los Alamos National Laboratory, National Centre for Atmospheric Research* and *Mprime)*
- Data Mining *(Generation 5, Canadian Security Establishment* and *Mprime)*
- Forests, Fires and Stochastic Modeling *(Ontario Ministry of Natural Resources, Tembec, Pacific Forests, the GEOIDE NCE* and *Mprime)*
- Marine Ecology *(Future of Marine Animal Populations* and *Tula Foundation)*
- Longitudinal Data Analysis in the Medical and Health Sciences *(GlaxoSmithKline* and *Toronto Western Hospital)*
- Climate Statistics in Agriculture *(Agriculture* and *Agri-Food Canada)*

Raising Canada's International Stature

The Canadian Statistical Sciences Institute will enhance the international stature of Canadian statistical research by providing:

- Opportunities for the world's best scientists to mix with Canadian researchers
- Infrastructure to attract renowned researchers to work in Canada
- Programs to attract outstanding students and early-career researchers

Typically, once a potential collaboration had been identified and a successful workshop had been held, most of the remaining funding was used to enable students to work with the scientific team. From this perspective, the NPCDS was very successful in developing new research teams, and enriched the Canadian statistical research enterprise by bringing statistical leadership to a number of interdisiciplinary teams.

Why a Canadian Statistical Sciences Institute?

The mathematical sciences institutes have made great strides in strengthening the infrastructure and international stature of the mathematical sciences in Canada over the past 20 years (see Chapter 4 for more details). For the health of the scientific enterprise in Canada, the statistical sciences community needs a similar mechanism to establish and coordinate a mix of research and training opportunities in the statistical sciences.

A Canadian statistical sciences institute would encourage international collaboration and communication among researchers, bring internationally renowned statisticians to Canada, and help attract the best and brightest minds to Canada's research pipeline. It would also advance the community's capacity for interdisciplinary research and help raise Canada's international profile in the statistical sciences. These gains would benefit not just statistical science, but also the many areas of scientific inquiry and economic activity that depend on quantitative analysis of this kind.

To serve the needs of the community, it is important that a major new statistical initiative be a national one—with the creation of diverse networks of statistical scientists working on important problems as one of its mandates. The statistical sciences research community in Canada is nationally cohesive, but it is also relatively dispersed. Some of the universities in larger centres have sizable faculty complements in statistics, but most statistics groups are fairly small. Researchers in smaller centres tend to be isolated to some degree. Nevertheless, they are needed to play a major role in advancing research, training HQP, and maintaining a steady flow of new research scientists. A Canadian statistical sciences institute—such as the proposed CANSSI—would link all these groups together, while ensuring a diversity of contributions to the Canadian statistical enterprise.

Statistics is fundamentally an applied discipline, driven in major part by new problems in science. For a great many statisticians, the passion surrounding their discipline is firmly intertwined with some specific scientific goal. Some subfields of statistical science are fairly well served by the existing mathematical sciences institutes, but statistical collaborations are more likely than mathematical teams to be interdisciplinary. Potential partnerships are also more likely to involve statisticians and scientists outside the NSERC umbrella, or outside academia altogether. CANSSI would provide an avenue to support this interdisciplinary characteristic, taking advantage of the head start provided by the NPCDS.

The statistical sciences community also sees a need for the recognition in Canada that statistical science has come of age as a discipline in its own right, and is of key importance to society. An important role of CANSSI would be to foster the visibility of the role of statistics within the sciences, government and industry. Nowadays many developments in the management and exploration of data happen outside of statistics, yet statistical principles are at the heart of effective data analysis. The activities of the proposed CANSSI would emphasize the fact that statistics plays a central role in many scientific disciplines and industries where data analysis and stochastic modeling are crucial.

An institute provides the infrastructure to get things done. It also provides the necessary leadership to organize important advances in research by spending concentrated time thinking and planning the development of research in the field. CANSSI would provide a focal point for this kind of planning. Just as importantly, it would provide leadership to maintain the quest for new funding by creating or taking advantage of all opportunities—local, provincial, national and international.

Proposed Activities of CANSSI

The CANSSI proposal outlines a portfolio of activities consistent with the LRP's pillars of people, research and discovery, and innovation and connection. These include:

- **Collaborative team projects** CANSSI would provide funding for core, interdisciplinary and applied research projects, and create the potential to further leverage resources and expertise through partnerships and national participation.
- **Thematic programs** CANSSI would contribute to the funding of thematic programs organized jointly with the mathematical sciences institutes in areas of overlapping interest.
- **Facilitation of networking** CANSSI would form network "hubs" for research subareas, such as statistics and its connections with probability, applied mathematics and computer science. Applied statistics hubs could include biostatistics, genomics, environmetrics, public policy, and the physical, health and social sciences. These networks of research activity would encourage and promote technology transfer, and provide windows into emerging research areas.
- **Training and mentorship** CANSSI would promote and develop proposals for workshops and summer schools for training and mentoring statistical scientists in collaborative research.
- **Innovation and connections** CANSSI would provide funding for graduate and post-doctoral internships. It would also facilitate connections with internship programs offered through the Mitacs-Accelerate program, Mprime and other relevant funding sources.
- **Reciprocal ties** CANSSI would form reciprocal ties and coordinate events with institutes around the world, building on the strong connections established between the National Science Foundation's (NSF's) Statistical and Applied Mathematical Sciences Institute (SAMSI) and the NPCDS.

Statistics Reaches for the Upper Bound

"Big data is the next big thing," reads the headline in the *Economic Times of India.* "Drowning in Numbers" says the *Economist* in its World Report for 2012. *Science* magazine offers a special issue on data in its Christmas gift offer of 2011. The International Statistical Institute has declared 2013 as the International Year of Statistics.

The opportunities for leading-edge research are limitless—as is the potential to attract the best to the HQP pipeline and to strengthen innovation in statistical science.

- **Emphasis on interdisciplinary research** CANSSI would advocate for more effective funding mechanisms to support research and training in interdisciplinary areas such as biostatistics and environmetrics. These are areas where worthwhile proposals are sometimes at risk of falling "between the cracks" of NSERC's mandate and those of the Social Sciences and Humanities Research Council (SSHRC) and the Canadian Institutes of Health Research (CIHR).
- **Enhancing the level of statistics in science and health research** CANSSI would reach out to agencies such as CIHR and Genome Canada to increase the representation of statisticians on review panels, institute boards and other advisory mechanisms.

Opportunities and Challenges

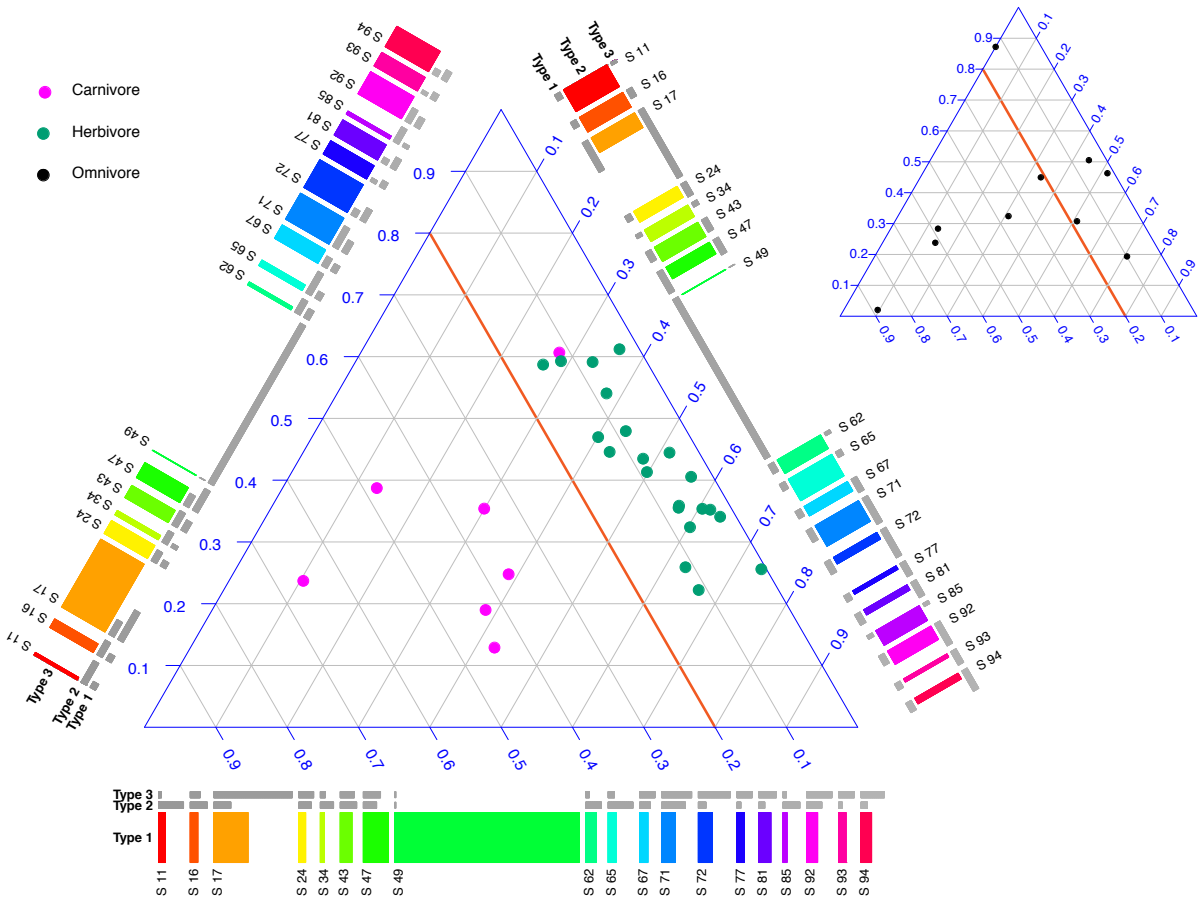
The time is particularly appropriate for the CANSSI initiative. Even as our society becomes increasingly aware of the importance of data, the quantity of available data is exploding much more rapidly than our ability to harness it. The demand for statistical expertise, and the need for statisticians to collaborate with applied mathematicians, computer scientists and subject matter scientists will only continue to grow.

The two most critical challenges for CANSSI to address are funding and visibility for statistical science. These go hand-in-hand. There is currently no new source of funding available through the NSERC Discovery portfolio, and funding may be constrained for some time to come. Even in a climate of increasing funding, the differences in approach between statisticians, applied mathematicians and computer scientists can be quite subtle to an external observer. In such a case, the value of a separate institute for statistical science may not be readily apparent. CANSSI would be able to take up where the NPCDS left off in raising awareness of the importance of statistical leadership in developing research and training initiatives in statistical science and collaborations.

Perhaps one of the most important functions of CANSSI would be to provide leadership in the advancement of the statistical sciences research agenda in Canada. Opening new opportunities to dramatically increase the numbers of students trained in statistical science and statistical collaboration will also be key.

Going Forward

With the launch of the CANSSI initiative, the statistical sciences in Canada are poised to enter a new phase. The CANSSI proposal has been submitted to the directors of the mathematical sciences institutes, and they have affirmed their support for the project. Discussions are underway towards an agreement on the terms of this support. Current thinking is to embed CANSSI within the institutes for the next funding cycle (2014–2019), on the assumption that NSERC funding for thematic and collaborative resources will not increase significantly during this time. CANSSI activities would be part of the proposals for funding submitted by the institutes in fall of 2013.



The CANSSI proposal outlines a detailed plan for governance and management of the institute, as well as ideas for additional sources of funding. Many areas of statistical science are also important for innovation in industry and government, and CANSSI would be closely involved with the institutes' innovation and industrial outreach efforts. It would also be a partner in the development of Mprime, as outlined in the next chapter.

Recommendation

The LRP Steering Committee makes the following recommendation:

- **Canadian Statistical Sciences Institute** The LRP Steering Committee strongly endorses the establishment of the Canadian Statistical Sciences Institute (CANSSI). In light of current constraints on resources, funding for CANSSI will need to be developed by working with the mathematical sciences institutes and Mprime, and by seeking additional funding outside the NSERC portfolio. Should resources become available within the Discovery Grant and thematic and collaborative resources portion of the envelope to support new thematic and collaborative resources, we recommend NSERC issue a call for proposals. We would expect CANSSI to respond to this call.

CHAPTER 6

Innovation and Connections

Overview

Canada's mathematical and statistical sciences communities have developed a vision to further engage with the most pressing problems in industry and government. To achieve this, we propose to build on the remarkable success of the Mprime Networks of Centres of Excellence (NCE), and a new proposal to combine the successful strategies of Mprime with the Research Partnerships Program at NSERC. Mathematical and statistical scientists are eager to engage with their industrial and government partners in furthering Canada's innovation agenda.

Innovation in its broadest sense—scientific, social and industrial innovation—allows societies to solve problems, seize new opportunities, and consequently achieve higher standards of living. We are currently witnessing several major technological and intellectual revolutions, as well as challenges that are profoundly restructuring our society and our economy. Rapid technological changes in biology and genetics are revolutionizing the medical sciences, leading to more complex models for biological systems. Increasingly complex structures of financial markets, their risks, their regulatory aspects and their management systems are dramatically altering the financial services sector and corresponding government legislation. The digital revolution is transforming all aspects of society, including communications, commerce, industry, health care and social services. Sustainability challenges are increasingly demanding rapid progress in science and technology to address questions regarding environmental and climate change, resource availability and energy management. And scientists, health care organizations, policy groups, government and industry are collecting overwhelming amounts of data, creating a need to extract information accurately and efficiently.

As we have emphasized throughout this document, the mathematical and statistical sciences are assuming new and important roles in addressing these challenges. The mathematical and statistical sciences provide a conceptual framework and a quantitative language for describing and measuring phenomena. They also provide the ability to understand systems that are:

- too complicated to study solely by observation, as is the case in economics, finance and biology;
- too large to contemplate with conventional tools, as is the case with the unprecedented quantity of available data and the speed with which it can be communicated;
- too fragile to disturb with experiments, as with the management of our natural resources; and
- too costly to deal with in an ad-hoc fashion, as with the implementation of large-scale transport and manufacturing systems.

Mprime NCE at a Glance

An outstanding record of success

- 43 national research teams
- 377 scientists in network
- 739 students
- 650 sponsors (private and public)

Mitacs and Mprime—Getting Started

To engage industry with the mathematical and statistical sciences, Mitacs and Mprime overcame several hurdles.

- Canadian companies often did not realize the potential of the mathematical and statistical sciences to address critical business opportunities, nor were they aware of the benefits of academic research in the quantitative sciences.
- The academic community, in turn, did not engage industry, government or other disciplines to identify and address those problems where mathematics and statistics could provide the methodologies to deal with complex problems, data and processes.
- Graduate students interested in advanced mathematical and statistical techniques had little opportunity to work on projects involving real-world problems that required sophisticated methodologies, and often left Canada to seek employment where they could utilize their training.

Mitacs and Mprime—Some Background

Innovation is what makes businesses thrive—yet Canadian businesses seem to lag behind the United States and other G7 countries, in spite of a serious and sustained effort by the Canadian government. Reviews of Canada's innovation performance undertaken by the Council of Canadian Academies (Council of Canadian Academies, 2009) and the Science, Technology and Innovation Council (STIC, 2008) point to "a serious issue facing Canada in terms of our country's lagging ability to capitalize on the knowledge we produce to create economic value."

Canada's mathematical and statistical communities are well aware of these challenges and of their own role and responsibilities in tackling them. A collective national effort was started by Canada's mathematical sciences community in 1997 to ensure that Canada would be in a position to leverage the power of advanced mathematical and statistical techniques, tools and methodologies in support of a broad spectrum of societal activity. Infrastructure to truly engage in academic-industry partnerships needed to be built, a sea-change in attitude in both business and universities needed to be fostered, and an army of young people needed to be trained. The NCE program was the ideal vehicle for such an ambitious project. The result was an amazing success story that reverberated across Canada and around the world.

The Mathematics of Information Technology and Complex Systems (Mitacs) NCE was created in 1998 to engage the mathematical and statistical sciences communities with Canadian society and industry, thereby helping to ensure that the full potential of the mathematical and statistical sciences was realized. Over the ensuing 13 years, Mitacs took a defining leadership role in developing a new model for academic-industry interactions, for training the next generation of researchers, and for opening channels for technology transfer and connections. The phenomenal success of this operational model led the network to develop and support a suite of unique programs geared toward collaborative industry-academic research and training projects, irrespective of discipline, sector or region.

As a result of this broadening mandate for training, in May 2011, Mitacs Inc. reorganized itself as two separate organizations, Mitacs Inc. and the Mprime NCE, each with its own focus and modus operandi. The two institutions are structured to work independently, but also in tandem as necessary, to support the country's innovation agenda. This restructuring has enabled Mprime to be totally focused on fulfilling the original mandate as Canada's Network of Centres of Excellence in the mathematical and statistical sciences.

Unfortunately, current rules guiding the NCE program called for an end to the participation of Mprime in this program as of March 31, 2012. The loss of this federal funding—about $5.4 million per year—will impact hundreds of companies, professors and students that have come together under the Mprime umbrella to address some of the most pressing challenges the country faces.

The Impact of Mprime on Research, Discovery and Innovation

With Mprime, the mathematical sciences community has developed the capacity to respond to emerging Canadian societal and economic needs for sophisticated mathematical tools and methodologies. Mprime currently supports 43 national research teams that draw on multidisciplinary expertise paired with societal receptors. The network focuses its resources on the five largest and most critical sectors of the economy as defined by Industry Canada: Biomedical and Health; Environment and Natural Resources; Information Processing; Risk and Finance; and Communication, Networks and Security.

The recent Council of Canadian Academies report, *The State of Science and Technology in Canada, 2012,* found that, "Canada's most rapidly growing research clusters are associated with networking and wireless technologies, information processing and computation, advanced data analysis, digital media technologies, speech and image recognition, carbon nanotubes and graphene, fuel cell technology, and space and planetary science" (Council of Canadian Academies, 2012). Notably, Mprime has supported projects in six of these eight emerging clusters.

The record is remarkable and admittedly unexpected. Hundreds of connections have been built between Canada's industrial base and the academic community. Eighty per cent of Mprime's current partners are from industry. These include small- and medium-sized enterprises, such as IT Interactive, Firebird, INVIDI Technology Corporation, Bliss Health Informatics and MARTEC. As well, several large companies, such as Banque Nationale du Canada, McCain Foods, EnCana Corporation, Lockheed Martin Canada, Bell Canada and Powerex Corporation, are active participants. Many companies such as SAS, Direct Energy, Symantec, SUN, Cloakware Corporation, MathWorks and Rogers Communications have participated in and helped to fund networking events. Over the years, the Mprime partners have contributed impressive amounts of cash towards the network's research—about $1.5 million per year from industry and the provinces.

Mprime's Research Record (2008–2011)

- 44 patents and licenses (completed and pending)—including an insertable cardiac monitor patented and licensed to Medtronic, and patents for optimizing energy management and pricing
- More than 50 software applications and copyrights—for example, PROMETHEUS, Canada's Wildfire Growth Simulator, and SRE, a customized implementation of the Vehicle Routing Problem
- A growing number of spinoff companies—including GridCentric, ExPretio and Sombra Labs

Source: (Mprime, 2012)

Mathematical Training—A+ in Industry

"Not all mathematicians with advanced degrees end up as researchers in mathematics. Many, like myself, end up in industry, where our training in abstract problem solving is potentially as important as in academia. Particularly in new and emerging fields, like computing was 40 years ago or data communications was 25 years ago, or the Internet was 10 years ago… the requisite industry-specific skills are not sufficiently available from university programs. So companies like AT&T then and Google now search for smart people with advanced degrees in math and physics, not because of their field of specialty, but because they are the best at finding answers to complex problems. The ability to logically and abstractly study problems is a critical skill."

Vaho Rebassoo, Former Chief Technology Officer, Boeing Information Technology, The Boeing Company

The Impact of Mprime on People

Another Mprime success story stems from its decisive contribution to Canada's shortage of highly qualified personnel (HQP)—81 per cent of NCE funds expended on the network's research have gone directly into student stipends. As a consequence, large numbers of students in the mathematical sciences who were looking to be trained in industrial outreach have found their home in Mprime projects. Many of them are now integrated as researchers within Canadian industry. In January 2011, Mprime took on the additional responsibility of training post-doctoral fellows to be able to address industrial imperatives, and today over 30 of these young people are directly engaged in academic-industry R&D. The tables below show the number of Mprime-sponsored trainees, and their retention rates in Canada, for 2008 to 2011.

Table 6.1 Number of Trainees (2008–2011)
In the three years between 2008 and 2011, Mprime trained well over 700 HQP each year.

	2008–2009	2009–2010	2010–2011
Research Associates	29	31	31
Post-doctoral Fellows	104	105	96
Technical Staff	12	5	7
Masters-PhDs	589	620	565
Undergrads	53	34	40
TOTAL	**787**	**795**	**739**

Table 6.2 Retention Rates (2008–2011)
The HQP trained through Mprime are finding employment in Canada.

Canadian Students	2008–2009	2009–2010	2010–2011
Employed in Canada	72%	70%	72%
Employed Abroad	25%	18%	26%
Unemployed	1%	2%	0%
Unknown	2%	9%	2%
Foreign Students	**2008–2009**	**2009–2010**	**2010–2011**
Employed in Canada	40%	40%	48%
Employed Abroad	50%	48%	48%
Unknown	10%	12%	4%

As the Mitacs NCE, Mprime launched the phenomenally successful Accelerate Canada internship program. This innovative program—which integrates industrial challenges into graduate research programs—has led to a paradigm shift in graduate training in many academic disciplines. Thousands of graduate students have participated in Accelerate, and the Government of Canada in its 2012 budget announcement acknowledged the importance of this program with an additional $14 million in funding. The Mprime NCE has now taken the lead in promoting and supporting the Accelerate internships program within the mathematical and statistical sciences.

Discussion—The Innovation Landscape without Mprime

As mentioned, federal funding for Mprime through the NCE program lapsed in April 2012, though limited management funds have been made available for two years beyond that date to wind down network administration, technology transfer and networking. The resulting loss of $5.4 million per year in federal funding and more than $1.5 million of leveraged funds from the private sector puts at risk:

- Canada's ability to utilize sophisticated mathematical and statistical tools and methodologies to address some of the most pressing problems of our time;
- the potential of the mathematical and statistical sciences communities to make a meaningful contribution to the emerging federal digital economy strategy;
- hundreds of linkages between Canada's industrial base and the academic community;
- very large numbers of current and future students in the mathematical and statistical sciences who are looking to be trained in industrial outreach;
- the long-term potential for mathematical and statistical sciences students to be integrated as researchers within Canadian industry;
- opportunities for Canada's mathematical and statistical sciences communities to continue to help energize the nation's innovation agenda; and
- the quality of research programs across the country, as the loss of funding erodes individual and team-based support systems.

It is imperative that the mathematical and statistical sciences communities address the "What comes next?" question for Mprime, so they can continue to contribute to Canada's innovation agenda, and to the other challenges facing Canada and the global community outlined earlier in this LRP.

Mathematics and Innovation

"Dan Hampson and I built our company, Hampson-Russell Software, from a start-up in Calgary employing three people in 1987 to a major international seismic software vendor with 50 employees and offices throughout the world. In 2002, we sold the company to VeritasDGC (now CGGVeritas) but we still run the company as an independent subsidiary. Our clients include every major oil and gas company in the world, and all of our software development is still out of Calgary. Both Dan and I use mathematics on a daily basis for the starting point of all of our software algorithms. Without mathematics behind us, our company would never have got off the ground. Truly, mathematics is the structure from which we built a world-leading geophysical software company."

Brian Russell, Vice-President, Hampson-Russell Software and Chair, PIMS Board of Directors

Unfortunately, current rules guiding the NCE program called for an end to the participation of Mprime in this program as of March 31, 2012. The loss of this federal funding—about $5.4 million per year—will impact hundreds of companies, professors and students that have come together under the Mprime umbrella to address some of the most pressing challenges the country faces.

Why Mprime Works

Mprime plays a broker role across the innovation cycle. Mprime is successful because it:

- Works with organizations to identify their challenges
- Helps identify scientists with the expertise to address these challenges
- Enables feedback loops to be maintained across a range of industrial contacts and stages of the research and innovation processes

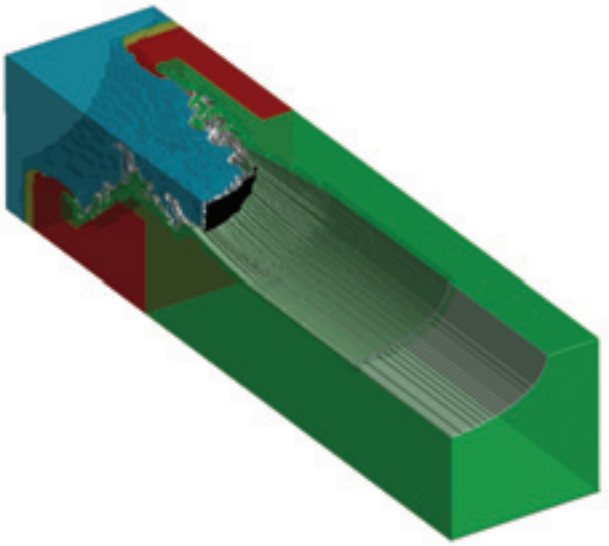
Opportunities and Challenges

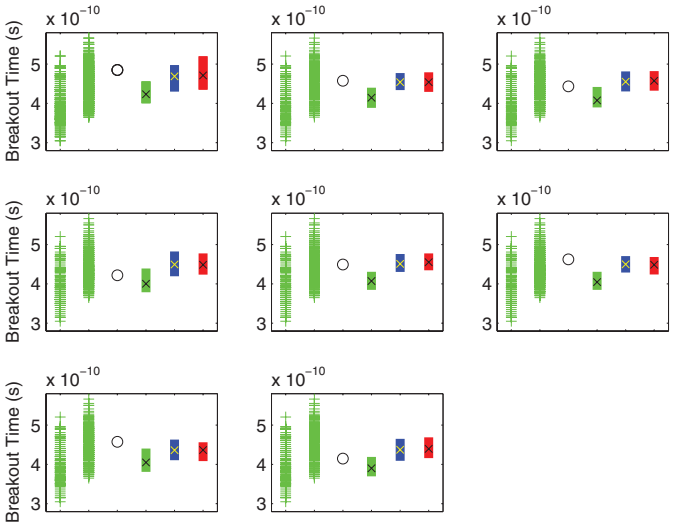
As the mathematical and statistical sciences communities look for new sources of funding for collaborations between academics, industry and government, a natural source to consider is NSERC's Research Partnerships Program (RPP). However, the current RPP programs at NSERC are not well adapted for industry collaborations with mathematical and statistical scientists. The ubiquitous aspect of the mathematical and statistical sciences can be a barrier to their acceptance in delivery-oriented federal programs.

For example, the Collaborative Research and Development (CRD) grants—the flagship program of RPP—are intended for well-defined projects undertaken by university researchers and their private sector partners. The criteria for these grants explicitly exclude support for what collaborative projects involving mathematical and statistical scientists often need most: a formal or informal group of researchers, with a broad range of different areas of expertise. Some researchers are needed at the development stage of a new product, some at the design phase, and some at the blue-sky "is this possible" stage.

Many university researchers in the mathematical sciences do not have well-defined private sector partners. This is, in part, because the mathematical and statistical sciences underpin research across the industry spectrum. It is also because the types of mathematical and statistical tools needed for certain industrial problems are not always clear, particularly to the industrial sponsor, but often not to the academic researcher either. Mprime is successful because it works with organizations to identify their challenges, and works with the academic community to identify scientists with the expertise necessary to address these challenges. This maintains the cycle from basic research through to applied research, innovation and final product across a range of industrial contacts.

The type of mathematics and statistics required by industry varies unpredictably and quickly. This creates a need for a continual feedback loop, from basic research to applied, and back again. To make this happen, a continual renewal of connections between industry, and a broad and deep pool of academic research expertise is a must. Industry time scales can be very short, whereas the research time scale is very long. For any single industrial partner, its interest in, and need for, mathematical or statistical expertise will vary unpredictably. There is also evidence that interactions work best via consortia, or groups of, industrial partners.





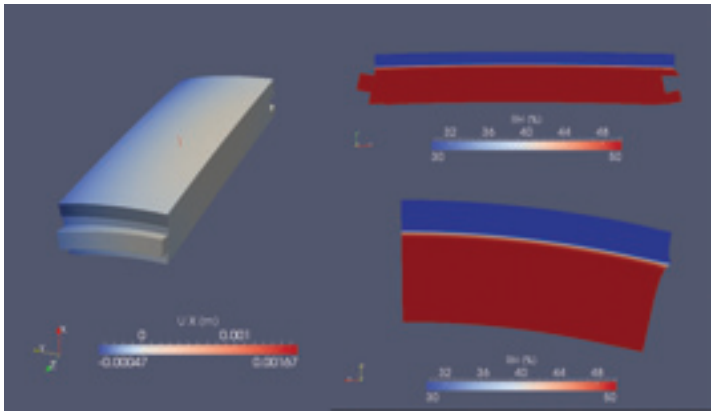
Going Forward

It is clear that an ongoing platform for seeding collaborations is essential to advance our communities' commitment to Canada's national strategy on innovation. Such a platform would also greatly enhance our communities' capacity to bring mathematical and statistical expertise to some of the most pressing problems of science, industry and government. It is critically important that the mathematical and statistical sciences communities capitalize on Mprime's industrial networks, and build on its successes.

The LRP Steering Committee agrees with the community consensus that the continuation of Mprime be anchored in the Canadian Network of Mathematical and Statistical Sciences Institutes. Mprime would continue as an independent entity, but function as the innovation arm of the new network of mathematical and statistical sciences institutes.

This arrangement would leverage the institutes' physical infrastructure to arrange for events like industrial problem solving workshops, interdisciplinary exploratory workshops and international connections. In turn, Mprime would serve as a national platform for the institutes' contributions to the country's innovation agenda and would support their industrial outreach. Mprime would also maintain close links with the Canadian Mathematical Society, the Canadian Applied and Industrial Mathematical Society and the Statistical Society of Canada.

Mprime has put forward a vision for its operation and activities: jointly managed and used by all stakeholders of the mathematical and statistical sciences communities, it will serve as a vehicle to engage both industry and government, and will take responsibility for coordinating industrial outreach



efforts of the Canadian mathematical and statistical sciences communities.

These objectives are clearly aligned with government priorities in all jurisdictions, and with the opinions of many leaders in the private sector regarding the need for Canada to become a leader in the knowledge-based economy. The most recent initiatives towards building a national digital economy strategy also speak to the need by government for outreach by our communities. Finally, it is also in line with the aspirations of the Canadian mathematical and statistical sciences communities, who are determined to elevate their game so as to ensure that appropriate and sustainable structures are in place to support both transformational research and a role in the country's innovation agenda.

Connections—Mprime as a Knowledge Transfer Network

The future role of Mprime that we envisage is to act as an overarching national innovation and knowledge transfer network. On the program side, it would bring together mathematical and statistical scientists from businesses, universities, research centres and financial and technology organizations to stimulate innovation through the mathematical and statistical sciences. On the funding side, it would provide a platform for the development of proposals to the RPP suite of programs. This platform would be similar to the RPP Engage program, in its goal of fostering the development of new research partnerships between academic researchers and companies. However, it would be more ambitious in its long-term goals to bring research innovation into industry.

Going forward, Mprime proposes to engage in a range of activities to support knowledge transfer and innovation. Mprime would provide the following:

- **A clearinghouse for industrial innovation connections** Mprime will maintain an operational capacity to quickly identify and support new areas of application where the mathematical sciences can have a major impact on the country's innovation agenda. It will continue to develop and maintain a database of mathematical scientists, existing and needed scientific expertise, as well as current and potential receptors and partners in the public and private sectors. Mprime has funded an enormous number of projects over its 13-year life. It will preserve and build on this database for future reference and use it towards its objectives.
- **Communications and advocacy for the mathematical and statistical sciences** Mprime will develop an intellectual and media capacity to communicate and advocate for the mathematical sciences, their impact, and their role in the country's innovation agenda. It will create a think-tank—the Centre for Mathematical Sciences Research Policy—and a media outlet to

document, formulate and communicate on a regular basis the role of the mathematical and statistical sciences within the innovation agenda.

- **Industrial outreach and training** Mprime will provide a platform for a nationally coordinated industrial outreach program, including industrial problem solving workshops, industrial and strategic post-doctoral fellowships, and highly relevant graduate learning and training programs for industrial mathematics. These will be geared to meet the immediate and emerging needs of both the academic and industrial communities.
- **International internships** Mprime will coordinate the Canadian effort in the North American mathematical research internship program, which will link graduate students and post-doctoral fellows in the mathematical sciences with business, industry and government agencies through focused collaborative research projects. The tri-national effort will be guided by, and will work closely with, Mitacs Inc. The program will be suitably adapted to optimize the global impact of the mathematical and statistical sciences, their universality, and their capacity to cross boundaries, whether they be disciplinary or geographic.
- **A national Internet infrastructure** Mprime will build—in partnership with Compute Canada—a national Internet infrastructure supporting mathematical and statistical sciences research and education. It will provide a unified video capture, video streaming and video storage service. It will define a national mathematics data backup service, and will coordinate a scientific computing infrastructure that can be used by all Canadian researchers. The expertise of Canada's mathematicians and statisticians will become a national resource that will help address the issues prompted by the emergence of big data sets.
- **Regional centres for mathematical biology** Mprime will partner with Health Canada, Agriculture Canada, Environment Canada, Natural Resources Canada and Transport Canada to continue its support for its regional centres in mathematical biology. It will coordinate a national vision for mathematical modeling of health and disease in biological systems. This will take priority within the portion of its mandate that calls for incubating and supporting major initiatives in emerging areas of the mathematical sciences deemed imperative and important to the national interest.
- **Support for the Canadian Statistical Sciences Institute and interdisciplinary research teams** Mprime will partner with Statistics Canada and Genome Canada to provide support for projects associated with the proposed Canadian Statistical Sciences Institute. Mprime will nurture and invest in interdisciplinary teams that combine depth in statistical science with expertise in substantive science, leading to the development of statistical methodology to answer important scientific questions in the health, social and natural sciences.

Recommendation

The following recommendation is directed towards NSERC in order to facilitate the federal government's continued investment in this important initiative for Canada's innovation agenda.

- **RPP Funding for Mprime** The annual envelope budget should be augmented by $1.5 million of Research Partnerships Portfolio funding in support of the mathematical and statistical sciences communities' research partnership efforts. This would enable the mathematical and statistical research communities—working through the institutes and through Mprime—to provide a platform for a wide range of successful collaborations with industrial partners. The Canadian Network of Mathematical and Statistical Sciences Institutes and Mprime would then prepare a detailed joint proposal for RPP funding, with the institutes coordinating their innovation and industrial outreach efforts through Mprime, and Mprime using the infrastructure of the institutes for its activities.

CHAPTER 7

Management and Implementation

Overview

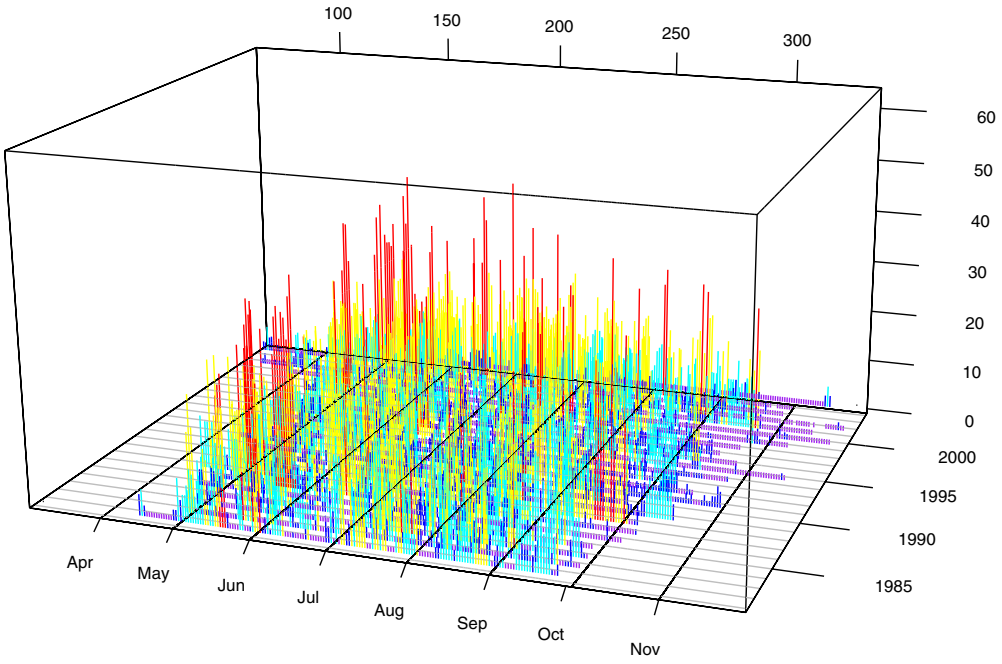
The establishment of a single Discovery Program funding envelope for the Mathematics and Statistics Evaluation Group and the recommendations in this Long Range Plan (LRP) provide an opportunity for ongoing dialogue with NSERC on the scientific ambitions and vision of our communities. To enable this discussion to continue, the LRP Steering Committee suggests that a committee of distinguished mathematical and statistical scientists be appointed to oversee the implementation of the plan. A key role for the committee would be to liaise with NSERC staff on a regular basis, and to represent the mathematical and statistical sciences communities to NSERC, and its committees and partners. In this chapter we provide our ideas for this LRP Implementation Committee.

Rationale

The development of this plan has given our communities an opportunity to articulate a vision for our science. The importance of research funding for individual investigators and for thematic and collaborative resources to achieving this vision must be underscored: our success in leveraging this funding, and in taking advantage of research opportunities in allied programs, has been vital to the growth in excellence in mathematical and statistical research across the country. The creation of our LRP offers us an opportunity to continue to involve mathematical and statistical scientists in leadership roles in liaising with our funding partners, including NSERC.

The allocation of the envelope funding will need to be reviewed over time. We have recommended in Chapters 3 and 4 that for the first five-year period a distinct boundary be created between Discovery Grant funding and thematic and collaborative resources funding. This responds to widely shared concerns among our colleagues about the creation of a single funding envelope. Even within the five-year window of this plan, and certainly within the next ten years, this boundary needs to be monitored to ensure that it is functioning in the best interests of all our researchers. For example, if the funding envelope were unexpectedly subject to a large increase or decrease, a LRP Implementation Committee could communicate quickly with our research communities and recommend the most appropriate mechanism for adjusting to this.

Our committee can imagine a number of scenarios that might change the landscape significantly from the one we are surveying today. Even seemingly minor decisions can have a large impact on science policy, and these impacts are sometimes



difficult to foresee. A committee of leading mathematical and statistical scientists charged with conducting ongoing dialogue with NSERC staff would be able to reflect these impacts back to NSERC on a steady basis. A LRP Implementation Committee would also be able to maintain regular dialogue with the directors of the mathematical and statistical sciences institutes to assess the functioning of the envelope model.

As documented in Chapters 1 and 2, there are many opportunities for the mathematical and statistical sciences in interdisciplinary research, both within the NSERC portfolio and across the Tri-council.[7] Members of a LRP Implementation Committee could be charged with seeking out opportunities for mathematical and statistical sciences research in interdisciplinary research.

In addition, a LRP Implementation Committee would maintain regular interaction with the Group Chair of the Mathematics and Statistics Evaluation Group. The Group Chair sits on the Committee on Grants and Scholarships, and so is tied into the NSERC committee structure and changes being implemented by the NSERC's Research Grants and Scholarships Directorate. A LRP Implementation Committee would provide support for the Group Chair on issues of research policy in the mathematical and statistical sciences.

7 The three granting councils—the Natural Sciences and Engineering Research Council (NSERC), the Social Sciences and Humanities Research Council (SSHRC) and the Canadian Institutes of Health Research (CIHR)—are sometimes referred to together as the Tri-council.

Roles and Responsibilities

The proposed LRP Implementation Committee would undertake the following roles and responsibilities:

- Review the Letters of Intent (LOIs) submitted in response to calls for proposals for thematic and collaborative resources.
- Make recommendations to NSERC and the Mathematics and Statistics Evaluation Group on the management of the funding boundary between the institutes and Discovery Grants in the envelope.
- Hold regular meetings with the Group Chair of the Mathematics and Statistics Evaluation Group.
- Engage with NSERC in consultations over potential members of the Institute Review Committee and Site Visit Committee, the Mathematics and Statistics Evaluation Group, the Executive Committee of the Mathematics and Statistics Evaluation Group, and other committees requiring expertise in the mathematical and statistical sciences.
- Monitor implementation of the LRP, and organize a mid-term review of the plan.
- Make recommendations on the timing of the next LRP and membership of the LRP Steering Committee.
- Seek out opportunities and synergies with other Evaluation Groups at NSERC, with Tri-council leadership and with other funding agencies.
- Work with Mprime and NSERC's RPP directorate to build capacity for the mathematical and statistical sciences in the partnership programs.
- Prepare regular reports for the mathematical and statistical sciences communities, summarizing activities of the committee and highlighting policy issues that need community input.
- Give presentations and updates to the communities through the Canadian Mathematical Society (CMS), the Canadian Industrial and Applied Mathematics Society (CAIMS) and the Statistical Society of Canada (SSC) and other outlets, as appropriate.

The policies governing the conduct of the LRP Implementation Committee would be the same as those governing the conduct of members of the selection committees, as detailed at http://www.nserc-crsng.gc.ca/NSERC-CRSNG/committees-comites/declaration-declaration_eng.asp.

Membership of the LRP Implementation Committee

The LRP Implementation Committee would have between eight and ten members, with balanced representation from applied mathematics, statistics and pure mathematics, as well as the interdisciplinary and international communities. The period of appointment would be three years, with approximately three members rotating off the committee each year. A chair and core executive group of approximately four members would be selected annually by the LRP Implementation Committee. The chair should not have a research proposal submitted to the Mathematics and Statistics envelope during the year he or she serves as chair.

One or more NSERC officials would serve as *ex officio* members of this committee. Appointment of all committee members would rest with NSERC. Suggestions for members would be solicited from the executive committees of the CMS, CAIMS and SSC, and from the communities at large.

Discussion

The Evaluation Group members, the Section Chairs and the Group Chair all play important roles in dialogue with NSERC about the concerns of the mathematical and statistical sciences communities. The annual workload for these individuals is substantial, and there is little time left for consideration of broader policy questions. An important role of the LRP Implementation Committee would be to consult with the communities and reflect these views on an ongoing basis.

It is a key concern of many, if not most, members of our communities that the limited resources in the Mathematics and Statistics envelope not become a source of friction between various interests. For example, any change in support for individual researchers from the Discovery Grants program should not take away resources from the institutes. This is the reason for our recommendation that the funding boundary between Discovery Grants and funds for thematic and collaborative resources be fixed for the first five years. Even with this guideline in place, some oversight would be needed. For example, in an extreme scenario and where the total amount of the envelope changed substantially, either by unexpected increases or decreases, it could be advisable to revisit this recommendation.

When mathematics and statistics were combined into a single Evaluation Group, community members expressed widespread concern about the relative calibration between statistics and mathematics of Discovery Grant proposals. This was especially the case among statistics researchers. This calibration has been closely monitored by the Evaluation Group executive and the Group Chair, and ongoing monitoring is recommended. The LRP Implementation Committee would dialogue with the Evaluation Group Executive Committee on this and other considerations for budget balancing

The LRP Implementation Committee would also be called upon to provide input to NSERC on how changes to the Discovery portfolio could have the most positive impact on our communities of researchers. As one example, the decision in 2011 to supplement the grants of early career researchers was welcome news, but scientists close to the ground would undoubtedly have welcomed an opportunity to provide input on this proposal in advance of its announcement. Another example is the suggestion from the CMS submission to the LRP that a program of "mini-accelerator" supplements could have a large benefit for our communities.

An important role for the LRP Implementation Committee would be to develop linkages among the mathematical and statistical sciences and with allied sciences, both at NSERC and across the Tri-council.

The Mathematics of Planet Earth initiative in 2013 is an example of an international research program that involves mathematical and statistical sciences institutes from around the world. The chair is Professor Christiane Rousseau of the Université de Montréal and the Centre de recherches mathématiques. This initiative represents a sustained effort to bring the tools of mathematical science to bear on global problems of sustainability, climate change, energy supply, natural resource management and health. Key goals will be to emphasize the role of the mathematical and statistical sciences in developing new approaches to tackle these challenges, and to create a context for interdisciplinary research in support of these efforts.

The International Year of Statistics, also to take place in 2013, is another example of a global effort to promote interdisciplinary research on societal challenges. Again, the LRP Implementation Committee could serve as an NSERC-based platform to highlight these programs and the opportunities they offer for interdisciplinary research.

Crosscutting initiatives are a feature of research programs at the NSF, and are typically created by program officers from two or more different directorates identifying and seeking funding for an important collaboration. At NSERC, opportunities for similar collaborations, developed by scientists representing different Evaluation Groups, is fairly limited. An important role of the LRP Implementation Committee would be to seek out such opportunities, to interact with representatives of other scientific communities, and to develop proposals to NSERC for new initiatives.

There are also many scientific opportunities for collaborations with the Canadian Institutes of Health Research and the Social Sciences and Humanities Research Council. Biostatistics, mathematical medicine, mathematical finance and econometrics are just a few of the areas that offer potential for this kind of collaboration. Again the LRP Implementation Committee could help to develop these collaborations at a level higher than the individual investigator. This would have the benefit of involving more

Crosscutting Initiatives

In 2010, the National Science Foundation (NSF) held a workshop on "Data-Enabled Science" to provide a high-level assessment of the needs and resource requirements for the mathematical and physical sciences around the "data deluge." As a result, a new program issued its first call for proposals in November 2011. Up to $5 million will be made available for Computational and Data-Enabled Science and Engineering in Mathematical and Statistical Sciences (CDS&E-MSS), jointly sponsored by the Division of Mathematical Sciences and the Office of Cyber Infrastructure. The funds will support fundamental research in mathematics and statistics in which the primary emphasis will be on meeting computational and data-related challenges. Another result of the workshop was a new requirement across the NSF for every proposal to include a detailed Data Management Plan.

people in the research conversation, as well as increasing the number and quality of proposals involving the mathematical and statistical sciences to programs that now exist, such as the Collaborative Health Research Projects program.

The opportunities for discussion, negotiation and consultation on initiatives with researchers in other disciplines are nearly unlimited. The success of the LRP Implementation Committee in this role would depend on the enthusiasm and energy of the committee chair and of a core group of members—the core might be different for different types of initiatives. We see this role of the committee as providing a presence for the mathematical and statistical sciences at a policy development level.

Recommendation

In order to realize the full potential of the LRP, and of our communities' aspirations to contribute to discovery and innovation in Canada, the LRP Steering Committee recommends:

- **LRP Implementation Committee** NSERC should establish a committee of leading mathematical and statistical scientists, chosen in consultation with the research communities, to oversee implementation of this Long Range Plan, represent the research communities to NSERC—and its committees and partners—and develop research linkages among the mathematical and statistical sciences, both at NSERC and the Tri-council, and with allied sciences.

CHAPTER 8

Detailed List of Recommendations

This chapter collects the recommendations from the report and adds some recommendations around process that are not specifically listed in the relevant chapters.

Research and Discovery (Chapter 3)

1. **Funding levels** NSERC should invest in Canada's mathematical and statistical sciences research via Discovery Grant levels that reflect the importance of the research base to Canada, and that acknowledge that the costs of research are similar to those in several related science and engineering disciplines. For example, computer science, operations research and theoretical sub-disciplines for several areas of science and engineering would be reasonable groups for comparison. This needs to take into account funding of HQP, potential supervision capacity, success rates and distributions, and international trends in supporting the mathematical and statistical sciences.
2. **Percentage of total funding** Under a scenario of stable funding, the new Mathematics and Statistics envelope should have a fixed percentage of its funds allocated for support of Discovery Grants. We recommend that this amount be 81 per cent for the next five-year cycle, based on a total annual Discovery Portfolio envelope for mathematics and statistics of $21 million.
3. **Undergraduate Student Research Awards** The LRP Implementation Committee should work with NSERC to develop more flexible rules around Undergraduate Student Research Awards (USRAs). In particular, mechanisms are needed to qualify a USRA-supervising professor without the requirement that he or she hold a current NSERC award.
4. **Team Grants** The LRP Implementation Committee should work with NSERC on creating more flexible rules for Team Grants. These rules could include a range of initiatives to increase support for small institutions, interdisciplinary proposals and pipeline programs.
5. **Process** The LRP Implementation Committee should work with NSERC to increase flexibility in programs and process, including:
    a. Exploring the possibility of stabilizing Discovery Grant funding, to avoid, as much as possible, large fluctuations from one competition year to another.
    b. Ensuring ongoing attention to the evaluation of interdisciplinary proposals: in particular the training of HQP in interdisciplinary research often has a different profile than disciplinary supervision, involving more co-supervision. In addition, a wide range of expertise is usually needed for evaluation of all the components, and reviewers chosen for their

expertise in one component may not themselves be involved in interdisciplinary research.

c. Discussing with the scholarships and fellowships directorate the possibility of announcing NSERC post-doctoral fellowship decisions earlier in the academic year.

d. Monitoring the impact on HQP assessments when delays in research activity are included in a Discovery Grant proposal. This is of particular, but not exclusive, concern for researchers increasing co-supervisions in anticipation of parental leave.

e. Clarifying the role of biostatistics research within NSERC's Discovery Grants and Scholarships portfolios. The community has expressed concern that research in biostatistics methods development within a larger program of health research may be ruled ineligible.

Thematic and Collaborative Resources (Chapters 4 and 5)

6. **Percentage of total funding for institutes** Under a scenario of stable funding, the new Mathematics and Statistics envelope should have a fixed percentage of its funds allocated for support of Canada's network of mathematical and statistical sciences institutes and the Banff International Research Station (BIRS). We recommend that this amount be 19 per cent for the next five-year cycle, based on the current annual budget of about $21 million for Discovery Grants and thematic and collaborative resources. Within this 19 per cent portion, we recommend that the percentage currently allocated to BIRS be reserved for its next competition.

7. **Long-term growth** The components of the envelope should have a capacity for long-term growth that reflects opportunities in the mathematical and statistical sciences and their own dynamics. The envelope structure in the long term should be able to reflect the substantial support that the mathematical sciences institutes and BIRS provide to other disciplines. In particular, NSERC should develop mechanisms that would permit partnering of resources between other Evaluation Groups and the Mathematics and Statistics Evaluation Group, in cases where the scientific arguments are compelling.

8. **Evaluation and renewal** Clear guidelines for renewal and evaluation of institute activities in the new envelope should be formally established by March 2013, so that evaluations conducted under new guidelines for the envelope can be completed in time to ensure continuity. Performance indicators that are appropriate for evaluating proposals for thematic and collaborative resources should be developed. The tables provided in Appendix B are a first step in that direction. The current NSERC funding cycle for the three mathematical sciences institutes ends on March 31, 2014. A recommended schedule and outline of procedures for the renewal process, modeled on recent competitions, is presented in Appendix B. The current

funding cycle for BIRS runs to March 31, 2016. A schedule and outline of the renewal procedure, modeled on recent competitions, is also presented in Appendix B.

9. **Canadian Statistical Sciences Institute** The LRP Steering Committee strongly endorses the establishment of the Canadian Statistical Sciences Institute (CANSSI). In light of current constraints on resources, funding for CANSSI will need to be developed by working with the mathematical sciences institutes and Mprime, and by seeking additional funding outside the NSERC portfolio. Should resources become available within the Discovery Grant and Thematic and Collaborative Resources portion of the envelope to support new thematic and collaborative resources, we recommend NSERC issue a call for proposals. We would expect CANSSI to respond to this call.

Innovation and Connections (Chapter 6)

10. **RPP Funding for Mprime** The annual envelope budget should be augmented by $1.5 million of Research Partnerships Portfolio funding in support of the mathematical and statistical sciences communities' research partnership efforts. This would enable the mathematical and statistical research communities—working through the institutes and through Mprime—to provide a platform for a wide range of successful collaborations with industrial partners. The Canadian Network of Mathematical and Statistical Sciences Institutes and Mprime would then prepare a detailed joint proposal for RPP funding, with the institutes coordinating their innovation and industrial outreach efforts through Mprime, and Mprime using the infrastructure of the institutes for its activities.

Management and Implementation (Chapter 7)

11. **LRP Implementation Committee** NSERC should establish a committee of leading mathematical and statistical scientists, chosen in consultation with the research communities, to oversee implementation of this Long Range Plan, represent the research communities to NSERC—and its committees and partners—and develop research linkages among the mathematical and statistical sciences, both at NSERC and the Tri-council, and with allied sciences.

Works Cited

Association of Universities and Colleges in Canada. (2011). *Trends in Higher Education, Volume 1: Enrollment.* Ottawa: AUCC.

Canadian Institutes of Health Research. (2011). *Strategy for Patient Oriented Research.* Ottawa: Canadian Institutes of Health Research. Retrieved October 17, 2012 from http://www.cihr-irsc.gc.ca/e/41232.html#b3

Canadian Mathematical Society. (2011). *The State of Canadian Mathematics: A 2010 Survey and Perspective.* Ottawa: Canadian Mathematics Society.

Council of Canadian Academies. (2009). *Innovation and Business Strategy: Why Canada Falls Short.* Ottawa: Council of Canadian Academies. Retrieved April 26, 2012, from http://www.scienceadvice.ca/en/assessments/completed/innovation.aspx

Council of Canadian Academies. (2012). *The State of Science and Technology in Canada, 2012.* Ottawa: Council of Canadian Academies. Retrieved September 27, 2012, from http://www.scienceadvice.ca/en/assessments/completed/science-tech.aspx

Dawkins, R. (2010). *Edge.* Retrieved May 8, 2012, from http://www.edge.org/conversation/who-is-the-greatest-biologist-of-all-time

European Mathematical Society. (2011). *Position Paper of the European Mathematical Society on the European Commission's Contributions to European Research.* Helsinki: European Mathematical Society.

Everhart, T. E., Green, M. L. and Weidman, S. (2011). Math Sciences 2025. *Notices of the AMS, 58,* p. 765.

Genest, C. and Carabarín-Aguirre, A. (2012). A digital picture of the actuarial research community. Technical Report, Department of Mathematics and Statistics. Montreal: McGill University.

Hu, G. C. (2012). Visualizing nanotechnology research in Canada: evidence from publication activities 1990–2009. *J. Technology Transfer, 37,* pp. 550–562.

Kuvda, R. (2011). Big Data, The Next Big Thing. *The Economic Times,* September 17, 2011.

Lustig, M., Donoho, D. and Pauly, J.M. (2007). Sparse MRI: The application of compressed sensing for rapid MR imaging. *Magnetic Resonance in Medicine, 58,* pp. 1182–95.

Mackenzie, D. (2012). A Flapping of Wings. *Science, 335,* pp. 1430–33.

McKinsey & Company. (2009). *McKinsey Quarterly.* Retrieved July 2012, from https://www.mckinseyquarterly.com/Strategy/Innovation/Hal_Varian_on_how_the_Web_challenges_managers_2286

Math Overflow. (2010). *Math Overflow.* Retrieved April 10, 2012, from http://mathoverflow.net/questions/2556/real-world-applicaitons-of-mathematics-by-arxiv-subject/

Mprime. (2012). *Knowledge Transfer.* Retrieved October 17, 2012, from http://mprime.ca/knowledge-transfer

NSERC. (2008). *Report of the International Review Committee on the Discovery Grants Program.* Ottawa: Natural Sciences and Engineering Research Council.

NSERC. (2012a). *Discovery Grants Competition Results.* Retrieved August 2, 2012, from http://www.nserc-crsng.gc.ca/Professors-Professeurs/DiscoveryGrants-SubventionsDecouverte/Index_eng.asp

NSERC. (2012b). *Facts and Figures.* Retrieved October 10, 2012, from http://www.nserc-crsng.gc.ca/NSERC-CRSNG/FactsFigures-TableauxDetailles_eng.asp

Pantula, S. (2011). Thriving with the NSF. *Notices of the AMS, 58,* p. 525.

Rehmeyer, J. (2011). Mathematical and Statistical Challenges for Sustainability. In Cozzens, M., & Roberts, F.S. (Ed.), *Report of a Workshop held November 15–17, 2010.*

Rowlett, P. (2011). The unplanned impact of mathematics. *Nature, 475,* pp. 166–169.

Statistical Society of Canada. (2011). *Report to the Long Range Plan Steering Committee.* Ottawa: Statistical Society of Canada.

Statistics Canada. (2012). *Table 477-0019—Public postsecondary enrolments, by registration status, Pan-Canadian Standard Classification of Education (PCSCE), Classification of Instructional Programs, Primary Grouping (CIP_PG), sex and immigration status, annual (number), CANSIM (database).* Retrieved July 31, 2012, from http://www5.statcan.gc.ca/cansim/

Steber, A. (2011). *CareerCast.* Retrieved April 12, 2012, from JobsRated: http://www.careercast.com/jobs-rated/2011-ranking-200-jobs-best-worst

STIC. (2008). *State of the Nation, 2008.* Ottawa: Science, Technology and Innovation Council. Retrieved March 28, 2012, from http://rd-review.ca/eic/site/stic-csti.nsf/eng/h_00011.html

Tibshirani, R. J. (1996). Regression shrinkage and selection via the Lasso. *Journal of the Royal Statistical Society, B. 58,* pp. 267–288.

Wigner, E. P. (1960). The unreasonable effectiveness of mathematics in the natural sciences. *Communications in Pure and Applied Mathematics, 13,* pp. 1–14.

APPENDIX A

LRP Steering Committee

Background

In June 2010, NSERC requested that the mathematical and statistical sciences communities prepare a long-range plan for a five- to ten-year horizon. The Mathematical and Statistical Sciences Long Range Plan Steering Committee was appointed in August 2010 by an advisory group consisting of the NSERC Mathematics and Statistics Liaison Committee, the presidents of the Canadian Mathematical Society (CMS), the Canadian Applied and Industrial Mathematics Society (CAIMS) and the Statistical Society of Canada (SSC), the directors of the mathematical sciences institutes, and NSERC staff. The meetings held by the LRP Steering Committee are listed at http://longrangeplan.ca/, along with other details about the work of the committee, its presentations to the societies, and its schedule for visits to many of the mathematics and statistics departments across the country.

The members of the Committee were:

Alejandro Adem	Director, Pacific Institute for the Mathematical Sciences
Edward Bierstone	Director, Fields Institute for Research in Mathematical Sciences
Eddy Campbell	President, University of New Brunswick
Charmaine Dean	Dean of Science, Western University
Christian Genest	Professor of Statistics, McGill University
Niky Kamran	Professor of Mathematics, McGill University
Rachel Kuske	Professor of Applied Mathematics, University of British Columbia
Mark Lewis	Professor of Mathematical Biology, University of Alberta
Nancy Reid	Professor of Statistics, University of Toronto (Chair)
Gail Ivanoff	Professor of Mathematics and Statistics, University of Ottawa, NSERC Evaluation Group Chair, *ex officio*
Anne-Marie Thompson	Director, Physical and Mathematical Sciences Division, NSERC, *ex officio*

The members of the International Advisory Committee were:

Mark Green	Professor of Mathematics, University of California, Los Angeles
James Berger	Professor of Statistics, Duke University
Jean-Pierre Bourgignon	Professor of Mathematics, Institut des Hautes Études Scientifiques, Paris

Terms of Reference:[8]

i. Context

At the request of NSERC, the Canadian mathematics and statistics communities will engage in a long range planning exercise over the next 15–18 months. A long-range plan (LRP) will allow the communities to identify areas of strength and establish a unified vision of priorities and directions for mathematics and statistics research in Canada. It will be used to inform NSERC and the Mathematics & Statistics Evaluation Group of the communities' priorities for research infrastructure, thereby allowing for the best use of resources to advance the work of the community as a whole.

The LRP exercise is a collaborative process and will reflect broad consultation with the communities. Key partners in this process include the Canadian Mathematical Society (CMS), the Canadian Applied and Industrial Mathematics Society (CAIMS) and the Statistical Society of Canada (SSC), as well as of the three Mathematical Institutes (Pacific Institute for the Mathematical Sciences (PIMS), the Centre de recherches mathématiques (CRM) and the Fields Institute) and the Banff International Research Station (BIRS).

ii. Purpose

The purpose of the Long-range Plan Steering Committee is to provide a framework for, and oversee the development of, the Long-range Plan for Canadian Mathematics and Statistics—a planning process to define communities' visions and identify a collaborative agenda for mathematics and statistics research in Canada over a five to ten year horizon.

iii. Governance, Operation and Financial Support

The LRP will be a process that is conducted by the mathematics and statistics communities and that is initiated by NSERC.

NSERC representatives will work closely with the LRP Steering Committee to provide Secretariat functions and logistical support to the Steering Committee.

NSERC will contribute towards the development of the LRP and will provide the Steering Committee and the Writing Panel with appropriate financial support for the purposes of organizing meetings, travel of Committee members to these meetings, collection of community input and the preparation of the LRP report.

iv. Long-range Plan Steering Committee

The composition of the committee is as follows:

Alejandro Adem, Edward Bierstone, Eddy Campbell, Charmaine Dean, Christian Genest, Niky Kamran, Rachel Kuske, Mark Lewis, Nancy Reid (chair), Gail Ivanoff *(ex officio)* Group Chair of the Mathematics and Statistics Evaluation Group, Anne-Marie Thompson *(ex officio)* NSERC Director, Research Grants, Physical and Mathematical Sciences Division.

v. Mandate

The mandate of the Long-range Plan Steering Committee is to provide advice and recommendations to ensure the LRP is representative, relevant and useful in the planning of long-term research and development for the mathematical and statistical sciences in Canada.

In carrying out this mandate, the Long-range Plan Steering Committee will:

- Provide overall direction for the management of the LRP process, including the budget, work plans, research and development issues to be considered, and timelines;
- Provide guidance on emerging trends and developments;
- Appoint a Writing Panel;
- Establish a collaborative web page for dissemination to, and input from, the relevant research communities;
- Elaborate a broad consultation strategy to solicit input;
- Prepare progress reports and the final Long-range Plan, as well as communications to the mathematics and statistics communities as appropriate;
- Ensure the LRP is completed in an efficient and timely manner.

8 The Terms of Reference for the Long Range Plan for Mathematical and Statistical Sciences Research in Canada and the LRP Steering Committee are provided verbatim. They are also available at http://longrangeplan.ca/

Writing Panel

The LRP itself will be formulated by a Writing Panel, which will be composed of an appropriate number of experts who will cover the main sub-disciplines reviewed by NSERC's Mathematics & Statistics Evaluation Group. The membership of the Writing Panel will be determined by the Long-range Plan Steering Committee and there may be some overlap with that of the Steering Committee.

Members of the Steering Committee will carry out the consultation strategy to solicit input and determine how this input will be reflected in the LRP. Primary input for the development of the LRP is expected to come from broad consultation with the Canadian mathematics and statistics communities, in part, through interaction with the scientific societies and institutes. It is expected that input will be solicited through a series of activities, such as the formation of sub-committees, advisory committees, presentations at open meetings and at town hall meetings, on-line discussion, and surveys. It is crucial that consultation and subsequent incorporation of the input into the LRP be achieved through a fair, transparent and rigorous process. These elements are critical to the overall success of the LRP.

Elements of the Long-range Plan

The LRP should reflect the following elements:

- Current and future scientific context;
  - How are current scientific developments affecting research in mathematics and statistics
  - How is research in mathematics and statistics impacting science
  - How does / should research in mathematics and statistics contribute to national science policy discussions
- How best to support the present programs of research;
  - How does existing infrastructure support research and training in mathematics and statistics
  - Are there opportunities for different mechanisms that would strengthen the support of research, for example, to facilitate greater collaboration
  - Are there important areas of research that are 'falling between the cracks', in terms of NSERC funding
  - Recognizing that adequate funding continues to be a struggle, is the current mix of resources suitable for research goals in mathematics and statistics
- The role of the Mathematical Institutes and BIRS as community resources;
  - How do current programs at the institutes impact research, training and recruitment in mathematics and statistics
  - What types of Institute initiatives might enhance their impact on research in mathematics and statistics
- Identification of important new initiatives and directions;
- How best to incorporate new initiatives into the research agenda;
- How best to leverage other research resources.

The LRP will also include assessments of the funding levels associated with these elements. While the LRP will be developed under an assumption of stable funding, it will identify both essential core items and priorities for enhanced investment under a scenario of modestly increased funding. The recommendations that will be made via the LRP must take into account NSERC's policies.

vi. Process and Time line

The Long-range Plan Steering Committee membership will be completed by the end of July 2010, and a kickoff meeting will be held shortly after to review the present Terms and Conditions and draw a work plan with specific objectives, activities and deliverables.

The Long-range Plan Steering Committee will meet as required for the duration of the planning exercise to provide oversight, approve work plans, approve progress reports and the final LRP, with a goal of completion by January 2012.

vii. Conflicts of Interest and Confidentiality

All members must strictly comply with the terms of the statement on ethics for NSERC selection committees and panels. Moreover, for the purpose of this exercise, a member will be considered to be in a situation of conflict of interest during a discussion on prioritization of a specific endeavour that would directly benefit the member or the member's organization.

APPENDIX B

Review of Proposals for Thematic and Collaborative Resources

The Mathematical Sciences Institutes

The Centre de recherches mathématiques, the Fields Institute for Research in the Mathematical Sciences and the Pacific Institute for the Mathematical Sciences, are currently funded through the Major Resources Support (MRS) program at NSERC. Funding for the three institutes has been extended through March 31, 2014 to accommodate the establishment of the new Mathematics and Statistics envelope. In the past, proposals from the institutes have been reviewed in a variety of ways, involving. for example, the Grant Selection Committees, the MRS panel, special review committees and site visit committees. We strongly suggest adhering to the five-year funding cycle, which is aligned with standard practices in North America.

Renewal of funding or new funding for thematic and collaborative resources should be determined by international peer review. To make the review effective, evaluators need to be knowledgeable about the mathematical and statistical sciences and have some familiarity with the role of institutes in our communities. The competition should be open, fair and transparent. It should allow for sufficient lead-time to prepare a proposal of the magnitude and scope that reflects the role played by an institute. Institute programs involve long-term commitments by large numbers of researchers and users, so site visits are an important part of the process.

Proposed Review Structure for Institutes

1. In a competition where proposals from the mathematical sciences institutes will be evaluated, NSERC will establish a four-member Institute Review Committee (IRC). It should be constituted by October 1 of the year before funding and consist of internationally renowned mathematical scientists knowledgeable about institute operations.
2. A call for letters of intent (LOIs) for proposals for thematic and collaborative resources to the Mathematics and Statistics envelope will be announced, and the LRP Implementation Committee will review the submitted LOIs and decide which should become full proposals, and then invite submission of those proposals.
3. In consultation with the Institute Review Committee, and with input from the applicants, NSERC will arrange for external review. When this process is complete, the Institute Review Committee will evaluate the proposals and decide which applications deserve further consideration.
4. In consultation with the Institute Review Commitee, and possibly soliciting suggestions from the applicants, NSERC will appoint a joint Site Visit Committee (SVC) to make visits that allow time for a proper evaluation of a major facility such as a mathematical sciences institute. We suggest two full days for each site visit. The Site Visit Committee will prepare reports on the visits, rank the applications and provide a funding recommendation.
5. The Institute Review Committee will consider the reports from the site visits as well as the evaluation of the proposals to rank the applications and submit a funding recommendation to NSERC.

The review process will follow a similar set of steps as in earlier funding cycles. The dates below are provided only

for concreteness, with the understanding that the precise timing will be coordinated in consultation with NSERC in early 2013.

Steps in the 2013–2014 Review of Proposals for Thematic and Collaborative Resources

June 2013	Call for letters of intent issued by NSERC
August 2013	Letters of intent submitted to the LRP Implementation Committee
November 2013	Deadline for full proposals
December 2013	Review of proposals completed, site visits scheduled
January 2014	Site visits
February 2014	Report and funding recommendations received from Site Visit Committee, and report and funding recommendations made by Institute Review Committee
March 2014	Funding decisions made by NSERC

Discussion

The LRP Steering Committee considered two alternative review mechanisms: 1) having the Institute Review Committee become part of the Mathematics and Statistics Evaluation Group, with one of the IRC members serving on the Evaluation Group Executive Committee during the year of the institutes' proposal submissions; and 2) having the Site Visit Committee serve as the only review committee involved in the evaluation of the mathematical sciences institutes.

Option 1 is very similar to the recommendation above, but has the logistical disadvantage of requiring coordination in timing with the review of Discovery Grant proposals. On the other hand, Option 1 would bring the evaluation of the institutes a little closer to our research communities if the Institute Review Committee worked alongside the Evaluation Group.

Option 2 does not seem satisfactory to the LRP Steering Committee: the Site Visit Committee is usually only involved during the week of the site visits, and the membership is typically nearly entirely international. We feel that a group of mainly Canadian researchers is needed to guide the process from proposal submission through to the funding recommendation.

The Banff International Research Station

The NSERC portion of BIRS funding comes from the Major Resources Support (MRS) program, and the current funding runs through to March 31, 2016. The review mechanism for BIRS should continue to be coordinated with its other major funders: the National Science Foundation (NSF), Alberta Innovates and the Consejo Nacional de Ciencia y Tecnología of Mexico (CONACYT).

Proposed Review Structure for the Banff International Research Station

1. In a competition year when a proposal from BIRS will be evaluated, letters of intent for (Canadian-based) collaborative multinational thematic proposals to the Mathematics and Statistics envelope will be assessed by the LRP Implementation Committee. It is expected that in 2015 there will be a single LOI, from BIRS, and that it will be accepted.
2. NSERC and the other major funders of BIRS will appoint a joint Site Visit Committee of internationally renowned scientists. The timing of the site visit will be coordinated with all the major funders of BIRS.
3. The recommendation on the award will be submitted by the Site Visit Committee to NSERC and the other major funders. The award decision and announcement will be coordinated by the four funding agencies.

Discussion

The review of BIRS is quite different from the review of the mathematical sciences institutes, both in the way it is coordinated among several funding partners, and in the nature of the proposal and its budget. Thus having the Site Visit Committee oversee the process of evaluation from beginning to end seems appropriate.

Evaluation of Institute Proposals

The LRP Steering Committee has developed a set of suggested evaluation criteria for institute proposals, adapted from NSERC's MRS criteria. These represent "first steps" in a process of preparing evaluation criteria. Such a process will probably take some time and should not be rushed. Comparisons with evaluation processes in other countries could also be helpful. Given the proposed calendar, there is sufficient time to work this out with NSERC before the next solicitation for new proposals.

Proposed Evaluation Criteria

1. **Added value of the resource**
   a. Not standard in a discipline in Canada and not **commonly available** in Canadian universities.
   b. **National** or **international** nature of the resource.
   c. Added value of the resource compared to **any** other Canadian resources that may be providing similar services.
   d. **Significant use** of the resource by a sufficiently large number of users (academic and non-academic) **throughout Canada, and significant international participation.**
2. **Use of the resource by the research community**
   a. Past (if applicable), current and projected level of use of the resource.
   b. Accessibility of the resource to, and actual use by, researchers (academic and non-academic users) beyond the host institution and region.
   c. Potential for collaboration with complementary Canadian or, if applicable, international resources.
   d. Extent to which the resource can accommodate the specialized needs of users.
   e. Demonstrated outreach to the potential Canadian or, if applicable, international academic and non-academic user communities.
3. **Need for access to the resource for the research programs**
   a. Impact of the resource on the advancement of the research programs of current and projected users and (when applicable) on the dissemination and use of the knowledge generated in the supported area(s) of research.
   b. Consequence of the loss of access to the resource on users' research programs.
4. **Merit of the research programs that rely on access to the resource and excellence of the user community**
   a. Quality, pertinence and impact of the past (if applicable), current and planned scientific activities, and significance of the research themes to the related communities.
   b. Excellence of activity organizers and users, and their level of commitment to the activities within the resource.
   c. Scientific (knowledge and technology) return on the investment in the resource.
5. **Demonstrated need for support through the Mathematics and Statistics envelope**
   a. Demonstrated need for, and effectiveness of, support through a grant from the Mathematics and Statistics envelope, as opposed to other NSERC grants and contributions from other sources.
   b. Nature and extent of the commitment and support from universities and other organizations.
   c. Justification of the requested funds from NSERC.
6. **Management of the resource**
   a. Effectiveness of management structure.
   b. Administration and allocation of access to the resource by different users (internal and external, from universities, government or industry).
   c. Plan and budget for maintenance and operation.
   d. Plan to keep abreast of scientific and technical advances, as well as to sustain well-coordinated and leading-edge research activities.
7. **Contribution of the resource to the training of Highly Qualified Personnel (HQP)**
   a. Importance of the resource for training, including unique training opportunities.
   b. Extent and excellence of training.
8. **Synergy**
   a. Extent to which a grouping of equipment, staff or participants enhances the value and capability of the resource and enables researchers to obtain results or carry out studies that would otherwise be very difficult or impossible.

Performance Indicators for Review of the Mathematical and Statistical Sciences Institutes

In November 2005, the mathematical sciences institutes provided a set of explicit performance indicators that had been developed in consultation with NSERC. The indicators were designed for the evaluation of the existing mathematical sciences institutes, as they viewed their activities in 2005. In response to LRP discussions and community consultations, the LRP Steering Committee has added some elements around diversity and interdisciplinarity that we feel should be part of a new set of performance indicators going forward. These suggested indicators will need further refinement, and are not yet appropriate for the review of thematic and collaborative resources in their full scope. They will also need to take into account the envisioned Canadian Statistical Sciences Institute and the Canadian Network of Mathematical and Statistical Sciences Institutes.

We recommend that the set of indicators provided below be reviewed with NSERC and revised, as appropriate, in time for the next funding cycle. These indicators should relate the activities and goals of thematic and collaborative resources to NSERC's selection criteria. The intent should be to provide measures that can be used to assess performance and gauge impact, guide program improvement and support accountability. Such measures should include both quantitative and qualitative indicators covering, for example, the scientific goals, efficiency, management objectives, highly qualified personnel (HQP) training and outreach of the resource. Overall, the indicators must address the question "What difference has the scientific activity made?"

2005 Performance Indicators Initiative

The following introductory text and table of indicators from 2005 are included in this LRP to provide a jumping off point for the future development of performance indicators. While some of the material provides historical context, many of the objectives remain relevant today, and should inform the development of indicators for the next five-year cycle.

Introduction

It is important in reading these performance indicators to bear in mind both the revolutionary nature of the change that has taken place in research and the evolving missions of the mathematical sciences institutes. Evaluators need also to be aware:

- that the institutes differ from each other;
- that they complement other institutions, like graduate mathematics departments, especially in areas of overlap such as HQP training;
- that the community looks to the institutes for leadership in many unexpected ways; and
- that there is movement towards establishing a national network of research and communication for mathematical and statistical research.

The role of NSERC funding in discovery mathematics research is crucial. Attempts to get community support for institute programs reveals that, in common with other basic sciences, this is the least understood part of the institutes' mission, and the hardest area in which to rally private sector support. By contrast, "partnerships and interactions" with other disciplines, both inside and outside the university, are widely encouraged. There is general understanding that the language and thinking of mathematics now form the underpinning of all the other scientific disciplines, and of many areas, like biomedicine, formerly thought not to be quantitative at all.

The institutes carry forward a strategic vision of Canadian mathematical science. Research institutes, which are to an extent free of traditional academic structures, are capable of innovation and leadership that transcend traditional disciplinary, institutional and even regional boundaries. Thus, within each of the four broad categories below are performance measures that reward complementarity with academic departments (and of course support by those departments), and measures of innovation on a large scale.

Definition of Activities, Outputs and Impacts

Activities	the functions performed or administered by the institutes and their participants
Outputs	the product of activities—the direct outcomes produced or directly controlled by the institutes
Impacts	the resulting outputs and outcomes produced by others and the consequent chain of outcomes which occur as a result of the activities

The general purpose of the performance indicators is to help document the impact of the mathematical sciences institutes and to assess to what extent they are meeting their objectives. The indicators listed in the attached table are derived from the institutes' objectives.

Each of the institutes will be reviewed periodically. The indicators will provide a framework for these assessments. The relative weight of each indicator will vary between institutes depending on the activities proposed to NSERC.

The indicators are meant to specify, for the institutes, the aspects on which they will be assessed. For peer reviewers, they will provide a framework in which to carry out their assessment. The indicators may also help to identify which activities have the greatest impact.

In using the indicators, it will be important to be able to relate as much as possible the outputs and outcomes resulting from the institutes' activities.

Mathematical Sciences Institutes Objectives

The mathematical sciences institutes aim to advance research in the mathematical sciences in Canada through the following objectives:

- Enhancing mathematical sciences research worldwide by
  - organizing high-quality research activities and networks within Canada
  - developing international connections for Canadian mathematicians
- Fostering partnerships and interactions
  - between mathematical science and other disciplines
  - between the university community (mathematical sciences) and other sectors (user sector)
- Training HQP in cooperation with Canadian universities
- Promoting mathematical science through educational activities and public awareness
- Developing and maintaining efficient management and infrastructure

The four main items could be described in slightly different terms as follows:

- Discovery and the advancement of knowledge
- Realizing the social, economic and cultural benefits of mathematical science
- Renewal of the scientific and technological workforce
- Education and communication

It is expected that the institutes will reach their objectives collectively. Their programs must complement each other and avoid duplication of effort. They must also, collectively, ensure a reasonable participation rate by the overall population of mathematical scientists in Canada. In addition, the institutes are expected to carry out their mission efficiently, and in the process develop an effective management structure and appropriate infrastructure.

Currently, NSERC funds are not used for activities in the fourth category of education and communication, and can be used only for those activities in the second category that are subsumed under discovery or training. Information about activities in categories not funded by NSERC is included in the indicators below with the understanding that it will not be used to influence the level of NSERC funding.

The institutes are expected to work in collaboration with relevant organizations, when appropriate, for instance in the domain of education, where most of the funding comes from provincial sources.

Note that the term "diversity" is used in this document in reference to creating an inclusive environment where researchers can interact with one another, and with the public, irrespective of differences such as gender, language and culture. It also refers to the value to Canadian researchers of participating in international collaborations that arise from participation in institute activities.

Performance Indicators—Mathematical Sciences Institutes (original 2005, updated 2012)

Objective	Activities	Outputs	Output Indicators	Impact (effect / influence)	Impact Indicators
Enhancing mathematical sciences research worldwide					
1. **Organizing high-quality research activities and networks within Canada**	• Thematic programs (year or six months) • General scientific activity (workshops, etc.) • Multi-investigator research activities • Lecture series • Publication programs • New initiatives (for example, national networks) • Commitment to diversity (e.g., gender, geography) in all programs	• New knowledge and original ideas • Excellent research results • High-quality research networks • Participation rates of diverse groups, at levels comparable with other North American math institutes • Competition for proposals (acceptance vs. submission rates for different activities)	• Publication counts • Patent counts • Peer assessment of quality and impact of publications • New collaborations among scientists	• Improvement in quality, profile and reputation of Canadian mathematical sciences • Improvement in quality, depth and diversity of research worldwide • Participation rates of diverse groups, at levels comparable with other North American mathematics institutes	• Trends in participation rates in institute activities • Trends in investments in institute activities • Evidence of influence of Canadian mathematical scientists involved in institute • Prestige for Canadian mathematics at international level
2. **Developing international connections for Canadian mathematicians**	• Same as #1 above • Proactive development of international collaborations and networks • Diverse recruitment of leadership and participation in international collaborations	• Excellent research results from collaborations • Collaborations resulting from the institutes' activities • New initiatives	• Number of new collaborations between Canadians and foreign researchers • Joint publication counts • Peer assessment of quality and impact of publications resulting from these collaborations	• Stronger links with other countries • Benefits to Canadian mathematical scientists, influence on base of expertise	• Trends in the number of Canadians participating in international initiatives • Trends in the number of mathematical scientists with international collaborations • Trends in the number of Canadians using institute programs to gain access to foreign science, and conversely
3. **Responding to the broader community**	• Balance of math, stats, applied math and outside disciplines • Committed ongoing dialogue with all communities for ensuring responsive programming broadly • Proactive development of activities with different communities	• Outputs in different areas at all levels—scientific, training, international • Leadership from different areas • Participation from different areas • Proposals from different areas	• As above in #1 and #2, in all areas	• Benefits and improvements as in #1 and #2, in all areas	• As above in #1 and #2, in all areas

Objective	Activities	Outputs	Output Indicators	Impact (effect / influence)	Impact Indicators
Fostering partnerships and interactions					
4. Linking the mathematical sciences and other disciplines	• Interdisciplinary thematic programs • Interdisciplinary general scientific activity • Interdisciplinary lecture series • Interdisciplinary collaborative research teams	• Research results of interest to other disciplines • Collaborations resulting from institute activities • Launching of new initiatives • Interdisciplinary training initiatives	• Number of new Canadian interdisciplinary collaborations • Joint publication counts • Peer assessment of quality and impact resulting from these collaborations	• Stronger, broader university research base • Stronger links with other disciplines • Trends in increased quality, depth, participation, prestige, increased access to interdisciplinary activities	• Trends in participation rates in institute activities • Trends in joint publications between Canadian mathematical scientists and researchers from other disciplines
5. Building partnerships between Canadian mathematics institutes and other institutes internationally	• Proactive collaboration / cooperation between institutes, within Canada and internationally • Connections / collaborations with organizations outside of math institutes • Cooperative training activities between institutes / organizations	• Increased collaborative and cooperative activities • New efforts to enhance institute coordination • New initiatives for training and collaboration • Complementary and non-repetitive activities	• Number of collaborative and cooperative activities • Diverse participation and leadership in activities • HQP trained through collaborative activities	• Better coordination of activities • Design of activities that are complementary • Coordinated training initiatives	• Number of participants in coordinated activities • Publications and collaborations resulting from coordinated activities • Feedback from participants
6. Linking the university and other communities (mathematical sciences and other sectors: user sector)	• Commercial / industrial seminars • Industrial problem solving workshops • Industry-oriented publications • International industrial connections • Facilitation for training and HQP connections leading to internships • Connections with public sector / government organizations	• Research results of interest to the user sector • Collaborations resulting from institute activity • Launching of new initiatives	• Number of new Canadian collaborations with the user sector • Number of reports to industry • Trends in areas of application of research projects • Trends in high-quality joint research with user sector	• Broader base of expertise in Canadian industry, universities • Stronger, broader university research • Stronger links among all sectors	• Trends in participation rates from user sector in institute activities • Investment in institute activities • Trends in joint publication, patenting • Creation of new companies

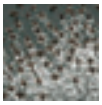
Objective	Activities	Outputs	Output Indicators	Impact (effect / influence)	Impact Indicators
Training of HQP in cooperation with Canadian universities					
7. Contributing to the education of graduate students and post-doctoral fellows (PDFs)	• Graduate courses during thematic programs • PDFs associated with thematic programs and collaborative research programs • Activities that reflect needs of mathematics, statistics and applied math • PDFs distributed at member institutions • Graduate summer schools • Professional development • Diversity participation at same levels as NSF-funded institutes	• HQP trained in areas of demand in the mathematical sciences • Complementarity with HQP training carried out in other sectors (universities and Mitacs) • Collaborative efforts with universities • Development of activities that support the pipeline across the country	• Number of personnel hired by university, industry or government • Trends in number of graduate students and breadth of training • Trends in numbers of PDFs • Tracking diverse participation	• Stronger, broader personnel base in Canadian universities and user sector • Increased employment opportunities for graduates / HQP • Increased international recruitment and repatriation of HQP	• Trends in hiring, salary levels, areas of expertise of HQP • Recruitment of institute-trained students and post-doctoral fellows at Canadian universities and abroad • Increased competition to participate in institutes programs

Objective	Activities	Outputs	Output Indicators	Impact (effect / influence)	Impact Indicators
Promoting mathematical sciences					
8. Promoting mathematical sciences through educational activities and public awareness	• Public lecture series • Education forums • Student conferences and seminars • Student competitions • Mentorship programs • Outreach programs for teachers • Press releases • Popular publications • Public poster campaigns • Leadership within the mathematical community • Commitment to diversity at levels comparable to NSF-funded institutes	• Science promotion activities for youth, Canadian communities and academic communities • Enhanced collaboration between mathematicians and educators	• Participation rates • Number and types of activities	• Increased quality and quantity of promotion activities • Increased reach • Increased interest in the mathematical sciences	• Changes in scope, quality and reach of activities • Changes in type of participants • Changes in the level of interest in the mathematical sciences

Objective	Activities	Outputs	Output Indicators	Impact (effect / influence)	Impact Indicators
Achieving efficient management and infrastructure					
9. Achieving efficiencies through partnerships	• Initiatives for matching funding • Complementary programs	• New cost-sharing partnerships through collaborations • Attracting industrial / public sector funding	• Amount of cost sharing • Number of activities supported through industrial funding • In-kind contributions	• Development of new funding sources for all activities • Cost saving through collaboration • Development of new directions for activities	• Increased activity using efficiencies • Number of new directions for collaboration • Greater visibility
10. Developing and maintaining efficient management and infrastructure	• Directorate structure and responsibilities clearly defined • Defined operating procedures for accounting, program staff, building management, and communications • Strategic planning	• Stable working environment • Efficient use of resources	• Quality of directorate appointments • Quality of staff appointments • Comparison of best practices across institutes	• Status and reputation of those involved with institutes	• Evaluations by visitors and participants • Survey of managers • Interviews with members of the mathematical community
11. Using electronic systems	• Web / online courses • Live streaming • Online collaboration • Social media • Efficient forms for tracking programs and participation	• Online activities • Work with community on uses of online tools • Programs to get people connected with new tools	• Number of online activities • Use of social media and online activities • Data tracking and communication of results	• New ways to reach variety of participants • Increased opportunities for collaboration • Better understanding of program success	• Increased types and number of participants • Publications and collaborations out of online activities • Details provided about program success

About the Photos

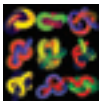
Cover: “Students.” Courtesy Thomas Hillen, University of Alberta. Mathematics and statistics students discussing research at the University of Alberta.



Page 2: “Bridging Individual and Collective Behavior.” Courtesy Ryan Lukeman, St. Francis Xavier University. This photo shows a typical flock of surf scoters moving on the water surface. Leah-Edelstein Keshet and her students study swarming behaviours by gathering high-quality data in the field, analysing the data and comparing the results to predictions from mathematical models. Reference: Ryan Lukeman, Yue-Xian Li and Leah Edelstein-Keshet (2010). *Inferring individual rules from collective behavior. PNAS,* 107 (28), p. 12576.

Page 11: “Sierpinski Meets Mondrian.” Courtesy Gerda de Vries, University of Alberta. The Serpinski Carpet is an example of a fractal, a pattern that continues to repeat itself as the viewer zooms in. In addition to having fascinating mathematical properties, fractal patterns are observed in nature, and have many applications in technology. The artist’s statement describes the vision behind this beautiful quilt. Web link for artist’s statement: http://www.telusplanet.net/public/gdevries/galleries/gallery/sierpinski-meets-mondrian.html

Page 19: “Mount Douglas Sunrise.” Courtesy Francis Zwiers, Pacific Climate Impacts Consortium. A February sunrise viewed from the top of Mount Douglas in Victoria, BC. This photo contains elements of the multiple interacting facets of the climate system—the atmosphere, ocean, land surface and even cryosphere. The silhouette of Mt. Rainier, which has extensive glacier ice, is visible on the horizon. The Garry Oak in the foreground is evidence of the carbon cycle. Potential external factors affecting climate also evident in the photo include the sun, the possibility of volcanic activity from Mt. Rainier and combustion products from aviation visible as the jet trail.



Page 31: “Loop Soup.” © Dror Bar-Natan, University of Toronto. An ideal knot is a knot tied with a shortest possible piece of a perfect rope—a rope that is perfectly flexible but also perfectly hard. These ideal knots were rendered in Mathematica and show all the knots with up to nine crossings. Web link for further references: http://www.math.toronto.edu/~drorbn/Gallery/KnottedObjects/LoopSoup/

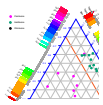
Page 33: “Students.” Courtesy Pacific Institute for the Mathematical Sciences. Students and faculty discussing research at the PIMS UBC site in Vancouver.

Page 45: “Dusa McDuff.” Courtesy Pacific Institute for the Mathematical Sciences. Professor McDuff presenting at the PIMS / UBC Distinguished Colloquium, November 2011.

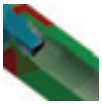
Page 53: “Treetime.” Courtesy William Casselman, University of British Columbia. This image was created for the first Fields Medal Symposium, held at the Fields Institute in October 2012 to honour Fields Medallist Ngô Bảo Châu and to bring the Langlands program to a wider audience. Professor Châu proved the Fundamental Lemma of the Langlands program. The simplest case of this Lemma counts points with alternating signs at various distances from the center of a certain tree-like structure. See this picture at the web page for the Symposium: http://www.fields.utoronto.ca/programs/scientific/fieldsmedalsym/12-13/

Page 54: “Marco Gualtieri.” Courtesy Centre de recherches mathématiques. Dr. Gualtieri presenting his André Aisenstadt Prize Lecture at CRM, April 2012.

Page 56: “Students.” Courtesy Pacific Institute for the Mathematical Sciences. Students and faculty discussing research at the PIMS UBC site in Vancouver.

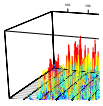


Page 63: “Clustering of Genomic Data.” Courtesy Hugh Chipman, Acadia University. Genomic interactions are clustered into three groups. The position along the edges of the triangle indicates membership weights in the three groups, and the bars along the edges describe the makeup of the groups. The goal is to develop new statistical methods to infer the metabolic composition of carnivore, omnivore and herbivore gut-microbiomes. Reference: Mahdi Shafiei, Katherine Dunn, Hugh Chipman, Hong Gu and Joseph Bielawski (2012). Bayesian inference of metabolic divergence among microbial communities, research paper under review.



Page 71: “Simulation of Radiative Shock.” Courtesy Derek Bingham, Simon Fraser University. Professor Bingham is collaborating with scientists at the University of Michigan’s Centre for Radiative Shock Hydrodynamics to understand the properties of radiative shocks, which occur naturally in astrophysical phenomena. Computer simulation of these shock waves is very expensive, but statistical methods enable experimental data to be combined with high- and low-fidelity simulations, leading to improvements in predictive capability and uncertainty quantification.

Page 72: “Deformation of Engineered Wood Flooring.” Courtesy André Fortin, Université Laval. Wood is a natural resource of paramount importance to the Canadian economy. The research project of Prof. Fortin illustrated here contributes to the development of wood products with high added value. The figure shows a simulation of the deformation of an engineered floor, magnified 10 times, due to fluctuations caused by seasonal humidity. Mathematical analysis is used to minimize these deformations and maximize the quality of the finished product.



Page 76: “Fire Weather Index.” Courtesy Doug Woolford, Wilfrid Laurier University. In Canada, fire management agencies use the Canadian Forest Fire Danger Rating System to assess fire risk. The Fire Weather Index (FWI) provides a measure for the potential intensity of a fire front. This figure depicts 25 years of daily FWI time series recorded at a fire-weather station in northwestern Ontario, using colour to represent risk categories. Developing and calibrating models for daily FWI behaviour is one of several research projects being conducted by a national network of statisticians, mathematicians, computer scientists and forestry researchers that includes partners from national and provincial forestry agencies.

Page 79: “The Water Planet.” Courtesy NASA. The Mathematics of Planet Earth 2013 is a multinational program of research and workshops, initiated by the mathematical sciences institutes in Canada.

Solutions
for a Complex Age

Long Range Plan for Mathematical and Statistical Sciences Research in Canada 2013–2018

For further information:

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