The State of Science and Technology in Canada, 2012

The Expert Panel on the State of Science and Technology in Canada

Council of Canadian Academies
Conseil des académies canadiennes

Science Advice in the Public Interest

THE STATE OF SCIENCE AND TECHNOLOGY IN CANADA, 2012

The Expert Panel on the State of Science and Technology in Canada

THE COUNCIL OF CANADIAN ACADEMIES
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Report Review

This report was reviewed in draft form by the individuals listed below — a group of reviewers selected by the Council of Canadian Academies for their diverse perspectives, areas of expertise, and broad representation of academic, industrial, policy, and non-governmental organizations.

The reviewers assessed the objectivity and quality of the report. Their submissions — which will remain confidential — were considered in full by the Panel, and many of their suggestions were incorporated into the report. They were not asked to endorse the conclusions, nor did they see the final draft of the report before its release. Responsibility for the final content of this report rests entirely with the authoring Panel and the Council.

The Council wishes to thank the following individuals for their review of this report:

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The report review procedure was monitored on behalf of the Council's Board of Governors and Scientific Advisory Committee by **Marcel Côté**, Founding Partner of SECOR Inc. The role of the report review monitor is to ensure that the panel gives full and fair consideration to the submissions of the report reviewers. The Board of the Council authorizes public release of an expert panel report only after the report review monitor confirms that the Council's report review requirements have been satisfied. The Council thanks Mr. Côté for his diligent contribution as review monitor.

Elizabeth Dowdeswell, O.C., President and CEO
Council of Canadian Academies

Executive Summary

A detailed understanding of the state of Canadian science and technology (S&T) is fundamental to decision-making related to S&T and innovation, and increasingly important in the rapidly evolving global S&T environment. The Government of Canada, through the Minister of Industry, requested the Council of Canadian Academies (the Council) to undertake an assessment of science and technology in Canada in order to answer the following question:

> *What is the current state of science and technology in Canada?*

Additional direction was provided through two sub-questions:

> *Considering both basic and applied research fields, what are the scientific disciplines and technological applications in which Canada excels? How are these strengths distributed geographically across the country? How do these trends compare with what has been taking place in comparable countries?*
>
> *In which scientific disciplines and technological applications has Canada shown the greatest improvement/decline in the last five years? What major trends have emerged? Which scientific disciplines and technological applications have the potential to emerge as areas of prominent strength for Canada?*

The Council appointed a multidisciplinary expert panel (the Panel) to address these questions. The Panel's mandate spanned the full spectrum of fields in engineering, the natural sciences, health sciences, social sciences, the arts, and humanities. It focused primarily on research performed in the higher education sector, as well as the government and not-for-profit sectors. The mandate specifically excluded an examination of S&T performed in the private sector (which is the subject of a separate Council assessment on the state of industrial research and development). The Panel's report builds upon, updates, and expands the Council's 2006 report, *The State of Science and Technology in Canada*.

ASSESSING THE STATE OF S&T IN CANADA

The concept of S&T strength is inherently complex and multidimensional and cannot be satisfactorily assessed using any single measure or indicator. Therefore, the Panel adopted a multi-lens approach, incorporating both qualitative and quantitative measures, including bibliometrics (the analysis of peer-reviewed scientific papers); two opinion surveys, one surveying the top-cited researchers in the world, and the other surveying Canadian S&T experts; technometrics (the analysis of patents); and an analysis of data related to highly qualified and skilled personnel (HQ&SP). Attempts to evaluate additional measures more relevant to the humanities, arts, and social sciences were hampered by lack of available data.

Comparisons and synthesis of the different methodologies were facilitated by the consistent use of a 22-field classification system covering all S&T. Although this classification system is the best available, like all field-based classifications it has limitations. These include the fact that it classifies scientific publications on the basis of the scientific journals in which the research is published, which may differ from the scientific discipline of the authors or traditional academic departments. Despite the inherent limitations of each type of evidence, the collective findings are comprehensive and represent one of the most in-depth examinations of Canadian S&T ever undertaken.

THE CURRENT STATE OF S&T IN CANADA

Canadian S&T, within the scope of this assessment, is healthy and growing in both output and impact. With less than 0.5 per cent of the world's population, Canada produces 4.1 per cent of the world's scientific papers and nearly 5 per cent of the world's most frequently cited papers. In 2005–2010, Canada produced 59 per cent more papers than in 1999–2004, and was the only G7 country with an increase above the world average.

Equally impressive has been the overall impact of Canadian S&T, as measured by Average Relative Citations (ARC) (a bibliometric measure of the frequency of citation of papers), by which Canada is ranked sixth in the world. On a field-by-field basis, Canada's ARC rankings placed it among the five leading countries in the world in 7 of 22 fields of research, and among the 10 leading countries in a further 14 fields.

These bibliometric measurements contribute to a high international regard for the quality and rigour of Canada's S&T. Among authors of the world's top-cited scientific papers, 37 per cent identified Canada as one of the five leading countries in their field, placing Canada fourth overall in the world, behind only the United States, United Kingdom, and Germany. Sixty-eight per cent rated Canadian research in their field as strong compared with the rest of the world. Many of these top-cited researchers also identified world-leading major research facilities and programs in Canada. For fields in the natural sciences, health sciences, and engineering there is a strong correlation between bibliometric impact, in terms of the share of the top one per cent most highly cited papers, and reputation, indicating the importance of the quality of scientific papers in the international perception of those fields. In contrast, there is no correlation between bibliometric impact and reputation for fields in the humanities, arts, and social sciences, indicating that for those fields other outputs that are not captured by bibliometrics (such as books and exhibitions) are more influential in determining reputation.

Canadian S&T experts also rated Canada's S&T enterprise as strong, although half of those surveyed considered Canada to have lost ground in the past five years.

Canada is part of a network of international S&T collaboration that includes the most scientifically advanced countries in the world. Canadian S&T attracts high quality researchers from abroad, with a sample of publishing researchers in 1997–2010 demonstrating a net migration of researchers into the country.

In contrast to the nation's strong performance in knowledge generation is its weaker performance in patents and related measures. Despite producing 4.1 per cent of the world's scientific papers, Canada holds only 1.7 per cent of world patents, and in 2010 had a negative balance of nearly five billion dollars in royalties and licensing revenues. Despite its low quantity of patents, Canada excels in international comparisons of quality, with citations to patents (ARC scores), ranking second in the world, behind the United States.

FIELDS OF RESEARCH IN WHICH CANADA EXCELS

The multi-lens approach adopted by the Panel provided considerable data on the magnitude, quality, and trends of S&T across fields. Since no single measure alone can be used to identify excellence, depending on the weighting given to each lens, different fields will emerge among the strongest.

The Panel determined two measures of quality, the field's international ARC rank and its rank in the international survey, to be the most relevant in determining the field's position compared with other advanced countries. Based on these measures of quality, the Panel identified six research fields in which Canada excels. These fields are (in alphabetical order):

- Clinical Medicine
- Historical Studies
- Information and Communication Technologies (ICT)
- Psychology and Cognitive Sciences
- Physics and Astronomy
- Visual and Performing Arts

Citation indices rank Canada among the top five countries in the world in five of these six fields. In five of these six fields Canada is also ranked among the top five countries in the world by leading international researchers. Three of the fields (Clinical Medicine, ICT, Physics and Astronomy) are among the five largest research enterprises in the country in terms of output of scientific papers, and the share of world publications in all fields except ICT has grown in 2005–2010 compared with 1999–2004. One of the fields, ICT, accounts for 44 per cent of Canada's patents. Notwithstanding the challenge of assessing research strength in the humanities, social sciences, and creative arts, three of the fields (Historical Studies, Psychology and Cognitive Sciences, Visual and Performing Arts) are at least partly, if not completely, within these disciplines. Collectively, these six fields of strength indicate the breadth of Canadian research excellence.

In addition to six fields of strength, the Panel identified nine sub-fields in which Canada leads the world in scientific impact, as measured by bibliometrics (ARC scores):

- Anatomy and Morphology
- Astronomy and Astrophysics
- Business and Management
- Classics
- Criminology
- Dermatology and Venereal Diseases
- General and Internal Medicine
- Nuclear and Particles Physics
- Zoology

Of these sub-fields, four (Anatomy and Morphology, Business and Management, Criminology, Zoology) are based in fields other than the six identified above. In a total of 56 sub-fields, 32 per cent of the 176 sub-fields studied, Canda is among the top five in the world according to ARC rank.

The data related to strengths in technological applications are less comprehensive, but indicate that Canadian patents related to ICT, Chemicals, and AgriFood have a greater impact than the world average.

GEOGRAPHIC DISTRIBUTION OF S&T STRENGTHS

Canada's most populous provinces, Ontario, Quebec, British Columbia, and Alberta, are the powerhouses of Canadian S&T, by all measures examined in this report. Together they account for 97 per cent of the total Canadian output in terms of scientific papers. Ontario produces 46 per cent of Canada's bibliometric output, in keeping with the 45 per cent of Canada's gross domestic expenditure on research and development (GERD) that is spent in Ontario. British Columbia is the leading province in terms of impact as measured by ARC.

The same four provinces are most often identified as provinces of strength by Canadian S&T experts, with Ontario most highly ranked in almost all sub-fields. These provinces also have the best performance in patent-related measures, and the highest per capita number of doctoral graduates.

Notwithstanding the dominant position of the four large research-intensive provinces, several fields of particular specialization were also identified in the other provinces, including Agriculture, Fisheries, and Forestry in Prince Edward Island and Manitoba; Historical Studies in New Brunswick; Earth and Environmental Sciences in Newfoundland and Labrador and Nova Scotia; and Biology in Saskatchewan. This diversity among provinces often aligns with local economic strengths and contributes to local and regional clusters of innovation.

IMPROVING AND DECLINING FIELDS OF S&T

This assessment is, in part, an update of the Council's 2006 assessment of the state of S&T in Canada. Results of the two assessments are not entirely comparable due to methodological differences such as the bibliometric database and classification system used in the two studies, and the survey of top-cited international researchers which was not undertaken in the 2006 assessment. Nevertheless, the Panel concluded that real improvements have occurred in the magnitude and quality of Canadian S&T in several fields including Biology, Clinical Medicine, ICT, Physics and Astronomy, Psychology and Cognitive Sciences, Public Health and Health Services, and Visual and Performing Arts. Two of the four areas identified as strengths in the 2006 report — ICT and health and related life sciences and technologies — have improved by most measures since 2006.

The other two areas identified as strengths in the 2006 report — natural resources and environmental S&T — have not experienced the same improvement as Canadian S&T in general. In the current classification system, these broad areas are now represented mainly by the fields of Agriculture, Fisheries, and Forestry; and Earth and Environmental Sciences. The Panel mapped the current classification system for these fields to the 2006 system and is confident that the overall decline in these fields is real, and not an artefact of different classifications. Scientific output and impact in these fields were either static or declined in 2005–2010 compared to 1994–2004. It should be noted, however, that even though these fields are declining relative to S&T in general, both maintain considerable strength, with Canadian research in Agriculture, Fisheries, and Forestry ranked second in the world in the survey of international researchers, and Earth and Environmental Sciences ranked fourth.

EMERGING AREAS

Although robust methods of identifying emerging areas of S&T are still in their infancy, the Panel used innovative bibliometric techniques to identify research clusters and their rates of growth. Rapidly emerging research clusters in Canada have keywords relating, most notably, to wireless technologies and networking, information processing and computation, nanotechnologies, and digital media technologies.

In another measure of emerging areas, Canadian S&T experts identified personalized medicine and health care, several energy technologies, tissue engineering, and digital media as areas in which Canada is well placed to become a global leader in development and application.

A SNAPSHOT IN TIME

This report provides considerable evidence that Canada's S&T enterprise is highly competitive internationally, with particular strengths in at least six fields of research, in several sub-fields, and in a number of rapidly emerging research clusters.

Although representing only a snapshot in time, this report can inform policy formulation and decision-making related to science, technology, and innovation by governments, academic institutions, and industry.

Contents

Appendices 1–9 are available online at www.scienceadvice.ca.

List of Abbreviations Used in the Report

ARC	Average Relative Citations
ARIF	Average Relative Impact Factor
AUTM	Association of University Technology Managers
AUID	Author Identification
BERD	business enterprise expenditure on research and development
CA	Collaboration Affinity
CFI	Canada Foundation for Innovation
CI	Collaboration Index
CIHR	Canadian Institutes of Health Research
CIPO	Canadian Intellectual Property Office
FQRSC	Fonds de recherche du Québec — Société et culture
GDP	gross domestic product
GERD	gross domestic expenditure on research and development
GI	Growth Index
HASS	Humanities, Arts & Social Sciences
HERD	higher education expenditure on research and development
HQ&SP	highly qualified and skilled personnel
ICT	Information and Communication Technologies
IP	intellectual property
IS	Interdisciplinarity Score
JPO	Japan Patent Office
NCE	Networks of Centres of Excellence
NRC	National Research Council Canada
NSERC	Natural Sciences and Engineering Research Council of Canada

OECD	Organisation for Economic Co-operation and Development
PCB	polychlorinated biphenyl
PPP	purchasing power parity
PSIS	Postsecondary Student Information System
R&D	research and development
S&T	science and technology
SR&ED	Scientific Research and Experimental Development
SSHRC	Social Sciences and Humanities Research Council of Canada
SI	Specialization Index
STIC	Science, Technology and Innovation Council
UCASS	University and College Academic Staff System
UNESCO	United Nations Educational, Scientific and Cultural Organization
USPTO	United States Patent and Trademark Office

Main Quantitative Indicators in the Report

(in alphabetical order)

Average Relative Citations (ARC): ARC is a measure of the frequency of citation of publications. An ARC score greater than 1.0 indicates that publications are more highly cited than the world average for that field or sub-field of research (all ARC scores are normalized by field of research). ARC is calculated for journal articles and for patents.

Bibliometric Cluster: A group of related journal articles closely linked through patterns in citation.

Growth Index (GI): The Growth Index is the rate of growth of publications between two periods of time.

IP Flow: IP flow is an indicator that was developed to assess cross-border flows of intellectual property. It measures the difference between the number of patents developed within a particular region and the number of patents currently registered or owned within that region.

Number of Patents: The number of patents registered with the United States Patent and Trademark Office (USPTO).

Publication Counts: Publication counts correspond to the total number of peer-reviewed journal articles published by a field or sub-field of research.

Specialization Index (SI): This indicator is a measure of Canada's concentration of research activity in particular research fields relative to other countries. An SI score greater than 1.0 indicates that more articles are published in that field or sub-field than would be expected based on world averages. SI is calculated for journal articles and for patents.

For a more detailed explanation of methods used in calculating each of these indicators, see Appendix 1.

1

Introduction and Charge to the Panel

- Charge to the Panel
- Building on the 2006 State of S&T Report
- Organization of the Report

1 Introduction and Charge to the Panel

Canada's economic prosperity, stability, and well-being in the knowledge-based economy of the 21st century has become increasingly dependent on its capacity to innovate — to create new knowledge and ideas and to translate them into goods, services, and policies that create wealth, enhance social foundations, and improve the quality of life.

Three broad elements characterize innovative societies: a world-class science and technology (S&T) enterprise; a highly educated and skilled workforce; and a business, regulatory, and social environment that encourages entrepreneurship and creativity. This report mainly addresses the first of these elements. A detailed understanding of the state of Canadian S&T is fundamental for governments, academic institutions, and industry in decision-making related to S&T and innovation. In what fields of S&T does Canada excel? How does Canadian S&T compare with the rest of the world? Are Canada's strengths concentrated in specific regions of the country? What are Canada's emerging strengths in S&T?

The answers to these and related questions depend upon assessing evidence that requires regular updating given the rapidly evolving global S&T environment, including the expanding S&T enterprise in emerging economies and the intense international competition for skilled personnel. There is also an increasing emphasis on the application of S&T to societal challenges, such as climate change, disease pandemics, and demographic shifts.

Internationally comparable S&T statistics are available from sources such as the Organisation for Economic Co-operation and Development (OECD). These data, however, are not sufficiently fine-grained to provide a detailed understanding of Canada's S&T strengths at the field level. This report therefore aims to provide a comprehensive, up-to-date assessment of the state of Canada's S&T at the field level. It builds upon, updates, and expands on *The State of Science and Technology in Canada*, a report released by the Council of Canadian Academies (the Council) in 2006. This report also complements the State of the Nation 2010 report of the Science, Technology and Innovation Council, which analyzed all the elements of Canada's innovation system against a series of indicators, but did not assess S&T strengths on a field-by-field basis (STIC, 2011).

The conclusions reached in this report are based on evidence from multiple sources, much of it generated by research initiatives undertaken by the Expert Panel on the State of Science and Technology in Canada (the Panel). This evidence is laid out in the results section of the report, its accompanying appendices, and, where indicated, in databases available from the Council. Despite the inherent limitations of each type of evidence, the collective findings are comprehensive and cohesive, and represent one of the most in-depth examinations of Canadian S&T ever undertaken.

1.1 CHARGE TO THE PANEL

To provide an updated assessment of the state of S&T in Canada — evidence that can underpin decisions at the national, regional, and institutional level — the Minister of Industry (the Sponsor) asked the Council to answer the following question:

> *What is the current state of science and technology in Canada?*

The Sponsor provided more direction through two sub-questions:

> *Considering both basic and applied research fields, what are the scientific disciplines and technological applications in which Canada excels? How are these strengths distributed geographically across the country? How do these trends compare with what has been taking place in comparable countries?*

> *In which scientific disciplines and technological applications has Canada shown the greatest improvement/decline in the last five years? What major trends have emerged? Which scientific disciplines and technological applications have the potential to emerge as areas of prominent strength for Canada?*

To address the charge, the Council assembled a multidisciplinary panel of 18 experts from Canada and abroad — the Expert Panel on the State of Science and Technology in Canada. Panel members were chosen for their expertise and experience. They served on the Panel as knowledgeable individuals in their own right, rather than as stakeholders for their region or area of expertise. Over the course of 12 months, the Panel met in person four times and also via teleconference.

At the beginning of the assessment process, the Panel met with Industry Canada representatives to ensure it fully understood the charge. At that time, the Sponsor provided further direction to the Panel:

- The primary focus of the charge is to assess Canada's current research strengths — and not its future needs.
- The assessment should span the full spectrum of fields in engineering, the natural sciences, health sciences, social sciences, and the arts and humanities.

- The assessment of Canada's research strengths should include a strong comparison with international peers.
- The report is to focus primarily on research performed in the higher education sector.[1]
- The interpretation of "geographically across the country" should be left to the Panel's discretion. The Panel chose the province or territory as the most meaningful geographic unit in Canada.

In response to the charge, the Panel worked towards developing a comprehensive assessment of the state of S&T in Canada, with a focus on research performed in the higher education sector, as well as in the not-for-profit and government sectors. The report assesses Canada's overall S&T strengths, as compared with international peers, and its strengths at the provincial and territorial level. (See Box 1.1 for definitions of "S&T" and S&T "strength".)

Box 1.1
Definitions

The Panel used the same definition of "S&T" as used in the 2006 report:

> The scope of S&T encompasses disciplines in the natural sciences (the study of nature); the social sciences, humanities, and health sciences (the study of human beings); and engineering (the creation and study of artefacts and systems). Our conception of S&T includes the myriad connections from science to technology and vice versa (CCA, 2006).

The Panel also adopted the 2006 report's definition of S&T "strength":

> There is no simple, one-dimensional measure of Canada's S&T strength. The concept is inherently multidimensional and encompasses (a) the quality of science and technology in Canada; (b) the magnitude or intensity of the Canadian effort in various domains of S&T; (c) the trend of the foregoing factors (are we gaining or losing ground?); and (d) the extent to which our S&T capabilities can be applied effectively to achieve social and economic objectives. Qualitative judgments that integrate multiple dimensions and factors are unavoidable (CCA, 2006).

1 Research and development (R&D) performed in the private sector is the focus of the Council of Canadian Academies' Expert Panel on the State of Industrial Research and Development in Canada (report forthcoming in 2013). For further details visit www.scienceadvice.ca.

1.2 BUILDING ON THE 2006 STATE OF S&T REPORT

In 2006, the Council of Canadian Academies published the first State of S&T in Canada report. This was the first assessment of its kind and provided a comprehensive evidence base for Canada's S&T strengths. The report identified four key areas of S&T strength for Canada: natural resources, information and communication technologies (ICT), health and related life sciences and technologies, and environmental S&T. As a direct impact of the Council's report, the federal government identified these strengths as areas of priority in the 2007 federal S&T strategy (Industry Canada, 2007).

Many lessons were learned from the 2006 assessment, which was completed in only 12 weeks due to the needs of the Sponsor. Particular strengths of the report were in its broad coverage of S&T including the social sciences and humanities, and in its integrated approach to assessing Canadian S&T. This included an opinion survey of Canadian S&T experts, bibliometric and technometric measures, and a "view from abroad" based on comments from international sources.

Lessons were also learned from the methodological approach on which the 2006 report was based:
- The different classification systems used for the questions asked in the opinion survey and the bibliometric analysis made it difficult to make precise comparisons between the two measures.
- In the interests of time, the Canadian opinion survey was sent broadly through "gatekeepers" and open to all, meaning there was no control over who completed the survey and how often each person completed it.
- The "view from abroad" was fairly restricted in that it was based on inputs from S&T counselors in embassies abroad.

Differences in scope between this assessment (see Box 1.2) and that of the 2006 assessment are that this Panel was asked about regional strengths, but not explicitly about infrastructure. In addition, the focus of this assessment is on research performed in the higher education sector as well as the public and not-for-profit sectors. Research in the private sector is being assessed in depth by another Council panel, the Expert Panel on the State of Industrial Research and Development. The mandates of the two panels are complementary and taken together will assess the entire S&T enterprise in Canada. This is a change from 2006 when the State of S&T report also covered research in the private sector.

Box 1.2
Scope of the Report

This report:
- Examines the magnitude, quality, and trends of S&T in Canada using multiple methodologies.
- Covers a broad spectrum of S&T, including the natural sciences, health sciences, engineering, social sciences, arts, and humanities.
- Focuses on research in the higher education, government, and not-for-profit sectors.
- Benchmarks Canadian S&T against other advanced countries.
- Provides a comprehensive evidence base for decision-making by governments, institutions, and organizations.

This report does not:
- Make recommendations or advocate policy.
- Include "value for money" calculations or judgments.
- Assess research in the business sector, or deployment or commercialization of technologies.
- Address the economic or social impact of research.

This new assessment aims to incorporate the strengths and the lessons learned from the 2006 report. On the one hand, the Panel wanted to ensure that its results and conclusions would be widely *comparable* to the 2006 findings, so as to facilitate a meaningful discussion of how Canada's S&T strengths have evolved in the past six years. On the other hand, the Panel sought to *improve* and *expand* on the 2006 research wherever possible. In particular, building on the strengths of the 2006 assessment, the Panel was more explicit in its interpretation of S&T and considered particular measures of strength in the humanities, arts, and social sciences. It also enhanced the multi-lens approach with new research methodologies. The next chapter describes the key research elements selected by the Panel, and how they compare with the research undertaken for the 2006 report.

1.3 ORGANIZATION OF THE REPORT

This report is divided into three main sections:
- **Background and context** for the report are provided in Chapters 1 to 3. Chapter 1 has described the charge to the Panel. Chapter 2 presents a discussion of the methodologies used and their limitations. Chapter 3 provides context for the report in terms of investment in research.

- **Results and evidence-based findings** are presented in Chapters 4 to 9. A multi-lens approach is used. Chapter 4 assesses Canadian research through bibliometrics; these quantitative results are complemented by qualitative data from two opinion surveys in Chapter 5. Chapter 6 uses advanced bibliometric techniques to examine Canadian S&T from the bottom up, and describes research clusters that are of high impact, large, or emerging in Canada. This chapter also looks at patterns of collaboration. Chapter 7 provides the results of a technometric analysis of patents and other related metrics. Canada's capacity to perform S&T is assessed in Chapter 8, through an analysis of highly qualified and skilled personnel and research infrastructure. Finally, in Chapter 9, Canadian S&T is examined at the provincial level.
- **A synthesis and conclusions** are provided in Chapters 10 and 11. Chapter 10 synthesizes the multi-lens findings for each field. Chapter 11 answers the questions posed in the charge to the Panel and draws together the Panel's overall conclusions and findings.

2

Methodology

- Classification of Fields and Sub-Fields of Research
- Overview of Methodologies used in the Report
- S&T's Contribution to Social and Economic Objectives
- Measuring Research in the Humanities, Arts, and Social Sciences
- Conclusions

2 Methodology

In selecting the methodologies for this assessment, the Panel sought to create a suite of complementary approaches and measures that would capture information about different aspects of the Canadian research system, including research outputs (e.g., publications, patents) and impacts (e.g., citations, reputation, training of students). The use of multiple methodologies was driven by the recognition that research strength is fundamentally a complex, multidimensional attribute that cannot be satisfactorily assessed by any single measure or indicator (CCA, 2012; Martin, 1996; see also Box 1.1 for the Panel's definition of S&T "strength"). The combination of quantitative data (such as bibliometrics) and expert opinion is increasingly recognized as the best available approach to assessing scientific performance across research fields (CCA, 2012). Quantitative indicators can provide a valuable check on expert opinion, and the inclusion of expert opinion ensures that aspects of research activity not amenable to quantification can still be considered in the assessment (Butler, 2007).[2]

The Panel aimed for a balanced combination of techniques, including well-accepted methodologies such as bibliometrics and opinion surveys, and newer approaches such as a bibliometric cluster analysis. In general, the Panel was informed by the 2006 State of S&T report, as well as other similar international reports (e.g., National Science Board, 2012; Royal Society, 2011; BIS, 2011; Battelle, 2010). This report also introduces new research elements and analyses that were not present in the 2006 report. Figure 2.1 summarizes the key research methods used in 2006 and 2012.

The next sections provide an overview of the methodologies used in the report (see the appendices[3] for more detailed information).

2 Two prominent examples of national research assessment initiatives that rely on this type of balanced combination of expert review and quantitative indicators can be found in the Australian national research evaluation system, Excellence in Research for Australia (ERA), and the new U.K. research assessment method, the Research Excellence Framework (REF) (see CCA, 2012; HEFCE, 2011; ARC, 2010).

3 There are nine appendices that supplement this report. These appendices are available as one electronic document for download, free of charge, from the Council's website, www.scienceadvice.ca.

Figure 2.1

Research Elements of the 2006 and 2012 Reports

The figure above illustrates the differences between the methodologies used for the 2006 report and those used for this report. Three of the four methodologies used in 2006 were repeated in 2012, and several new methodologies were used as well. Bibliometrics refers to the study of patterns in peer-reviewed journal articles. "Advanced" bibliometrics refers here to the use of additional techniques to study clusters of related research as well as patterns in research collaboration. Technometrics is the analysis of intellectual property (i.e., patents).

2.1 CLASSIFICATION OF FIELDS AND SUB-FIELDS OF RESEARCH

To draw comparisons among the results derived through the different methodologies, and to integrate the findings, a common classification system was required. For this purpose, the Panel chose a new classification system developed by Science-Metrix[4] (Archambault *et al.*, 2011) that includes 22 research fields composed of 176 sub-fields (see Table 2.1). This classification system better reflects the current landscape than the main alternative — that used by the National Science Foundation for its *Science and Engineering Indicators* (e.g., National Science Board, 2012) — which is now several decades old. The Science-Metrix system also includes more fields in the humanities, arts, and social sciences. This classification was used for all bibliometric analyses, opinion surveys, and analysis of highly qualified and skilled personnel (HQ&SP), but not for the analysis of patents and related measures as the organization of data in the patent database made this impractical.

Table 2.1

List of Fields and their Sub-Fields in the Classification System used in this Report

Agriculture, Fisheries & Forestry	Biology
• Agronomy & Agriculture • Dairy & Animal Science • Fisheries • Food Science • Forestry • Horticulture • Veterinary Sciences	• Ecology • Entomology • Evolutionary Biology • Marine Biology & Hydrobiology • Ornithology • Plant Biology & Botany • Zoology
Biomedical Research	**Built Environment & Design**
• Anatomy & Morphology • Biochemistry & Molecular Biology • Biophysics • Developmental Biology • Genetics & Heredity • Microbiology • Microscopy • Mycology & Parasitology • Nutrition & Dietetics • Physiology • Toxicology • Virology	• Architecture • Building & Construction • Design Practice & Management • Urban & Regional Planning **Chemistry** • Analytical Chemistry • General Chemistry • Inorganic & Nuclear Chemistry • Medicinal & Biomolecular Chemistry • Organic Chemistry • Physical Chemistry • Polymers

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4 Science-Metrix is a Canadian company specializing in bibliometric analyses.

Clinical Medicine

- Allergy
- Anesthesiology
- Arthritis & Rheumatology
- Cardiovascular System & Hematology
- Complementary & Alternative Medicine
- Dentistry
- Dermatology & Venereal Diseases
- Emergency & Critical Care Medicine
- Endocrinology & Metabolism
- Environmental & Occupational Health
- Gastroenterology & Hepatology
- General & Internal Medicine
- General Clinical Medicine
- Geriatrics
- Immunology
- Legal & Forensic Medicine
- Neurology & Neurosurgery
- Nuclear Medicine & Medical Imaging
- Obstetrics & Reproductive Medicine
- Oncology & Carcinogenesis
- Ophthalmology & Optometry
- Orthopedics
- Otorhinolaryngology
- Pathology
- Pediatrics
- Pharmacology & Pharmacy
- Psychiatry
- Respiratory System
- Sport Sciences
- Surgery
- Tropical Medicine
- Urology & Nephrology

Communication & Textual Studies

- Communication & Media Studies
- Languages & Linguistics
- Literary Studies

Earth & Environmental Sciences

- Environmental Sciences
- Geochemistry & Geophysics
- Geology
- Meteorology & Atmospheric Sciences
- Oceanography

Economics & Business

- Accounting
- Agricultural Economics & Policy
- Business & Management
- Development Studies
- Econometrics
- Economic Theory
- Economics
- Finance
- Industrial Relations
- Logistics & Transportation
- Marketing
- Sport, Leisure & Tourism

Enabling & Strategic Technologies

- Bioinformatics
- Biotechnology
- Energy
- Materials
- Nanoscience & Nanotechnology
- Optoelectronics & Photonics
- Strategic, Defence & Security Studies

Engineering

- Aerospace & Aeronautics
- Automobile Design & Engineering
- Biomedical Engineering
- Chemical Engineering
- Civil Engineering
- Electrical & Electronic Engineering
- Environmental Engineering
- Geological & Geomatics Engineering
- Industrial Engineering & Automation
- Mechanical Engineering & Transports
- Mining & Metallurgy
- Operations Research

General Arts, Humanities & Social Sciences*

- General Arts, Humanities & Social Sciences

General Science & Technology*

- General Science & Technology

Historical Studies

- Anthropology
- Archaeology
- Classics
- History
- History of Science, Technology & Medicine
- History of Social Sciences
- Paleontology

* General Science and Technology and General Arts, Humanities, and Social Sciences are fields formed for the bibliometric classification to capture articles published in multidisciplinary journals such as *Nature* or *Science*.

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Information & Communication Technologies	Mathematics & Statistics
• Artificial Intelligence & Image Processing • Computation Theory & Mathematics • Computer Hardware & Architecture • Distributed Computing • Information Systems • Medical Informatics • Networking & Telecommunications • Software Engineering	• Applied Mathematics • General Mathematics • Numerical & Computational Mathematics • Statistics & Probability **Philosophy & Theology** • Applied Ethics • Philosophy • Religions & Theology
Physics & Astronomy	**Psychology & Cognitive Sciences**
• Acoustics • Applied Physics • Astronomy & Astrophysics • Chemical Physics • Fluids & Plasmas • General Physics • Mathematical Physics • Nuclear & Particles Physics • Optics	• Behavioural Science & Comparative Psychology • Clinical Psychology • Developmental & Child Psychology • Experimental Psychology • General Psychology & Cognitive Sciences • Human Factors • Psychoanalysis • Social Psychology
Public Health & Health Services	**Social Sciences**
• Epidemiology • Gerontology • Health Policy & Services • Nursing • Public Health • Rehabilitation • Speech-Language Pathology & Audiology • Substance Abuse **Visual & Performing Arts** • Art Practice, History & Theory • Drama & Theater • Folklore • Music	• Criminology • Cultural Studies • Demography • Education • Family Studies • Gender Studies • Geography • Information & Library Sciences • International Relations • Law • Political Science & Public Administration • Science Studies • Social Sciences Methods • Social Work • Sociology

Limitations of the Classification System

All S&T classification systems have limitations, and the system used in this report is no exception. It was designed for use in bibliometric analyses and does not necessarily correspond with departmental or institutional structures. As an example, the field of Historical Studies includes the sub-fields of Anthropology, Archaeology, Classics, History, History of Science, Technology and Medicine, History of Social Sciences, and Paleontology. All of these are undoubtedly "historical" studies, but within a traditional university may be spread among the faculties of arts, humanities, social sciences, and natural sciences.

For bibliometrics, publications within each of the 22 research fields are classified *on the basis of the journals in which they appear*, and not on the basis of the specific scientific nature of the research reported or the departmental affiliations of the authors. Thus, for example, papers published in the *New England Journal of Medicine* are assigned to the field of Clinical Medicine, even if the subject material is in basic biomedical science, clinical epidemiology, population health, health services, health economics, or the history of medicine. To put this particular example into a Canadian context, the field of Clinical Medicine used in the classification encompasses a broader range of research than does the Clinical Research pillar (pillar 2) of the Canadian Institutes of Health Research (CIHR). This pillar is limited to clinical research on humans, and excludes studies of human disease mechanisms and processes performed in cells, systems, or animal models of disease that do not involve the direct participation of human subjects. Because of these differences in definitions, the number of papers classified in the field of Clinical Medicine in this report is considerably higher than would be expected based solely on pillar 2 research supported by CIHR. Similar examples will be seen in other disciplines. These kinds of effects are unavoidable as the classification system used here is designed to effectively categorize the global scientific establishment, and not to align with the specific discipline definitions or institutional structures of any particular country. Such a system is necessary in order to be able to compare Canadian research with the rest of the world.

The other related challenge that inevitably surfaces with any scientific classification system is how to address interdisciplinary or multidisciplinary research. To some extent, all such classification systems fail to do justice to research that spans multiple disciplines since such research typically encompasses two or more traditional academic fields. This problem has long been recognized in bibliometric research, but in the past there have been few alternatives to relying on traditional disciplinary categories. However, new techniques are now emerging that allow bibliometricians to identify clusters of related research based on such factors as keywords and cross-citations (Kostoff *et al.*, 2007; Klavans & Boyack, 2010). While these techniques are still experimental to a degree, they appear to capture patterns in interdisciplinary work. An analysis of Canadian research activity based on these techniques is explored in Chapter 6 of this report.

2.2 OVERVIEW OF METHODOLOGIES USED IN THE REPORT

2.2.1 Bibliometric Analysis

Bibliometrics, in this context, refers to the study of patterns in scientific publications in a database — namely peer-reviewed articles in academic journals. Many such analyses have been undertaken in the past to benchmark and compare scientific performance across countries. As one example, in 2004, U.K. scientist Sir David King published an influential paper in *Nature*, analyzing the scientific impact of nations. King used data based on scientific articles published in peer-reviewed journals to draw inferences about the relative importance and impact of research carried out in selected countries. In particular, he focused on a country's share of the top-cited one per cent of scientific papers as an indicator of the overall level of impact associated with research activity in that country (King, 2004). While King was hardly the first to use bibliometric data to analyze and compare research internationally, this study did much to promote the use of bibliometric indicators, and their use has grown significantly in the intervening years.

Many countries now undertake periodic assessments of their scientific activity based — at least in part — on bibliometric data. The United States publishes its biennial *Science and Engineering Indicators*, which includes a large compilation of data on publication output in various fields of science across countries (e.g., National Science Board, 2012). The United Kingdom's Department for Business, Innovation and Skills publishes a biennial assessment of the U.K.'s research base, which relies on bibliometric data (e.g., BIS, 2011). The Netherlands produces a biannual report analyzing the performance of the Dutch scientific establishment (NOWT, 2010). Finland uses bibliometric data in its periodic assessments of the State and Quality of Scientific Research in Finland (Academy of Finland, 2009), and Australia uses bibliometric indicators in its national science assessment exercise, Excellence in Research for Australia (ERA) (ARC, 2010). These are merely a few examples. It is increasingly rare for countries *not* to undertake periodic monitoring and assessment of scientific research that rely at least partially on bibliometric indicators.

As a mode of research assessment, bibliometric analysis has several important advantages. First, these techniques are built on a well-developed foundation of quantitative data. Publication in peer-reviewed journals is a cornerstone of research dissemination in most scientific and academic disciplines, and bibliometric data are therefore one of the few readily available sources of quantitative information on research activity that allow for comparisons across many fields of research. Second, bibliometric analyses are able to provide information about both research *productivity* (i.e., the quantity of journal articles produced) and research *impact* (measured through citations). While there are important methodological issues associated with these metrics (e.g., database coverage by discipline, correct procedures for normalization and aggregation, self-citations, and negative citations, etc.), most bibliometric experts agree that, when used appropriately, citation-based indicators can be valid measures of the degree to which research has had an impact on later scientific work (see Moed, 2005 for a review of these types of indicators). One particularly important issue is that all citation-based indicators should be field-normalized (CCA, 2012; REPP, 2005; Moed, 2005) because different research fields have different citation cultures. For example, papers in Biomedical Research and Clinical Medicine tend to cite a large number of other studies, whereas papers in fields such as Mathematics and Statistics tend to cite comparatively fewer references (Moed, 2005). The differences among fields need to be taken into account in the construction of these indicators. All citation-based indicators used in this report are field-normalized; the number of citations of Canadian research is compared only to the number of citations internationally in that specific field or sub-field.

Although bibliometric data were also used in the 2006 report, for the current study the Panel selected both new variables and techniques and a different source of bibliometric data (Elsevier's Scopus database rather than the Web of Science database now maintained by Thomson Reuters) due to its comparatively greater coverage of the humanities and social sciences. The Panel commissioned a comprehensive, bibliometric analysis of Canadian and world publication trends to inform this assessment. Through a competitive bidding process, the Canadian firm Science-Metrix was selected to provide this analysis. The resulting research was extensive. It included consideration of many different bibliometric indicators for assessing Canada's scientific performance relative to its international peers, as well as advanced techniques such as the identification of clusters of related research and an analysis of researcher migration.

Findings from the bibliometric research are presented in several sections of the report, most prominently in Chapters 4 and 6. Unless otherwise stated, bibliometric results, figures, and tables show Canada's position compared with the top 20 countries by scientific volume, including the world. Additional details on the bibliometric methodology can be found in Appendix 1, and supplementary bibliometric data for selected countries in Appendix 3.

Limitations of Bibliometrics

The limitations of bibliometrics fall into three main categories. First and most importantly, all bibliometric indicators are based on only one type of research output — peer-reviewed articles published in journals. This inherent limitation (which is more acute for disciplines where the peer-reviewed article is not the standard mode of research dissemination) is discussed in detail in Section 2.4. Second, the results of bibliometric analysis are influenced by both the choice of classification system (discussed in Section 2.1) and database. The Panel chose to use the Scopus database because it has greater coverage of journals in the humanities, arts, and social sciences than the main alternative — the Web of Science.

Although the Scopus database currently covers 19,500 journals,[5] it does not capture every journal published in Canada. As a result, some portion of Canada's research output does not factor into the analysis (just as some portion of the research output of every country is not captured in these databases). In addition, while Scopus does include journals and publications in many languages, there is a general bias in the database towards English language journals (Archambault *et al.*, 2006). As a result, journals published in French may be under represented (this problem tends to be more acute for fields in the humanities, arts, and social sciences — see discussion in Section 2.4). The third main type of limitation stems from constraints associated with the actual construction of the indicators. Citations typically serve as the basis for indicators that gauge research impact. One of the most informative bibliometric measures is the Average Relative Citations (ARC) index — a measure of the impact of research based on how many times it has been referenced relative to other research in that field. Yet it takes time for the impact of research to be registered in new citations — both due to the time required for an awareness of new research to build and the time associated with the research publication process. In order to allow for this fact, for research in the natural sciences, health sciences, and engineering, a two-year lag time is introduced (i.e., the analysis of ARC for the 2005–2010 period includes articles published only up to and through 2008). As citations take longer to accrue in the arts, social sciences, and humanities, a four-year lag time is used for research in these areas. (See Appendix 1 for more details on the construction of the bibliometric indicators used in this study.)

2.2.2 Technometrics

Patent statistics and indicators are now routinely used by the Organisation for Economic Co-operation and Development (OECD) and other international organizations in comparing and assessing S&T outputs across countries. The 2006 S&T report also relied on these indicators to provide insights about Canada's capacity in technology development. To capture information about Canada's patent stock and production of intellectual property relative to other advanced economies, the Panel commissioned a full analysis of Canadian and international patent holdings filed with the U.S. Patent and Trademark Office (USPTO). USPTO data were selected for this analysis because the USPTO is arguably the most important patent and trademark office for Canadian patent filers. (During the period 2005–2010, Canadians accounted for 18,000 patented inventions in the USPTO, but only 12,000 at the Canadian Intellectual Property Office (CIPO).) The 2006 report also used technometrics based on USPTO data, ensuring comparability between the results of the two reports.

5 http://www.info.sciverse.com/scopus/scopus-in-detail/facts.

Science-Metrix also carried out the technometric research, and constructed technometric indicators that mirrored the bibliometric indicators. Results for the technometric analysis are presented in Chapters 7 and 9. Additional details on the technometric research methodology can be found in Appendix 7.

Limitations of Technometrics

Despite being relatively easy to assess using quantitative data, patent data have important limitations as a measure of strength in applied research and technology development (see NRC, 1997 for a full discussion of limitations). One key weakness of these measures is that not all types of technology development lead to patentable technologies. Some, such as software development, are typically subject to copyright instead. This is particularly relevant for research fields where software development may be a key aspect of developing new technologies such as computer sciences or digital media. Even when patenting is applicable as a means of commercializing and protecting intellectual property (IP), not all inventions are patented. Some are protected in other ways, and firms may seek to capture the value of their inventions through lead-time advantages and marketing strategies rather than IP protection. At the other end of the spectrum, some organizations file patents simply to block competitors from pursuing a line of research. These factors add uncertainty to interpretation of patent data — and warrant caution in interpreting such data as an indicator of strength. Perhaps the most important weakness of patents and intellectual property indicators, however, is that they represent only one aspect of the larger process of research commercialization, technology development, and the adoption of improved practices. They do not necessarily reflect either the magnitude of the research and development that went into a particular technology or the later stage activities necessary to bring a new technology to market. Patents also all have different commercial value. As a result of these limitations, patent-based indicators should by no means be regarded as a measure of *all* aspects of applied R&D and technology commercialization. Yet they remain a useful and informative measure of at least one type of applied R&D output, and shed some light on the areas of technology development in which Canadian institutions are most active. Patent-based indicators also support international comparison of the results. Newer methods are emerging, such as the examination of key words in the titles of published technology books (Alexopoulos & Cohen, 2010), but the Panel felt that at this stage its objectives were better served by the use of existing technometric and bibliometric analysis.

2.2.3 Opinion Surveys

The quantitative indicators discussed above do not capture information about the full range of Canadian S&T activity and strengths. As a result, in order to complement these indicators, the Panel also commissioned two large-scale surveys to gather opinions from researchers in Canada and around the world on the state of Canadian S&T.

Survey of Canadian S&T Experts

A major part of the evidence-gathering process for the 2006 report was a survey of Canadian S&T experts, undertaken to gather perceptions of Canadian research strengths and weaknesses. For the purposes of comparability, the Panel chose to repeat that survey, but with three key changes:

- The invitation to participate in the survey was sent only to a pre-selected group of target respondents,[6] rather than through an open survey invitation such as that used for the 2006 assessment. This change was designed to ensure that those responding to the survey really were experts in Canadian S&T.
- To allow comparisons with the bibliometric analyses, the survey was based on the taxonomy of scientific fields and sub-fields provided by Science-Metrix (see Table 2.1).
- A new question added to the survey asked respondents to identify areas of provincial S&T strength, to directly address the aspect of the charge related to geographical distribution of strength.

In this survey, Canada's performance is benchmarked against other advanced countries.

Survey of the Top-Cited International Researchers

To obtain the opinions of global S&T experts regarding Canada's S&T strengths, the Panel undertook a survey of the authors of the world's top-cited peer-reviewed articles. This was a new addition to the methodology used in 2006.

The Panel worked with Science-Metrix to identify the top-cited one per cent of all articles in each field of research (using the same classification system as for the bibliometrics study — see Table 2.1) in 2000–2008. For five fields — Built Environment and Design, Historical Studies, Visual and Performing Arts, Philosophy and Theology, and Communications and Textual Studies — the top one per cent yielded an insufficient sample size. As a result, the samples for these fields were

6 See Appendix 6 for full details. The sample included fellows of the Royal Society of Canada, Canadian Academy of Engineering, Canadian Academy of Health Sciences, Canada Research Chairs, technology transfer managers, federal government science leaders, etc.

expanded to the top five per cent of cited articles. This exercise resulted in an initial list of over 72,000 highly cited research papers, from all fields of study and with authors from around the world. Once duplicate email addresses were removed, the target survey population was reduced to 53,954 highly cited authors who were invited by the Panel (by email) to participate in an online survey (once bounce backs were excluded, the survey was received by 44,868 email addresses). Survey invitations were sent in August and September of 2011. The survey, which comprised four short questions plus biographical information, was designed to take less than five minutes to complete. Each recipient was asked to (a) identify their field and sub-field of research, (b) identify the top five countries in the world in their sub-field of research, (c) rate Canada's overall research strength in their sub-field, and (d) identify any world-leading research facilities or programs in Canada in their field.

The Panel selected EKOS Research Associates Inc., the market research and opinion firm that assisted the Council in the administration of the 2006 survey of Canadian S&T experts, to administer both opinion surveys. The main findings from the surveys form the basis of the discussion in Chapter 5 on the reputation and stature of Canadian research. Data on emerging fields are presented in Chapter 6, infrastructure in Chapter 8, and provincial results in Chapter 9. Additional methodological details and data from these surveys, including the full text of both surveys, are presented in Appendices 5 and 6.

In this survey, Canada's rank is benchmarked against the entire world, and its measure of strength is benchmarked against other advanced countries.

Limitations of the Opinion Surveys

There are limitations related to the use of opinion surveys generally. The most important of these is simply that their results are, in the end, based entirely on the opinions of those surveyed. As pointed out in the 2006 State of S&T report, there are many reasons to believe that expert perceptions of the type examined in these two surveys provide valuable insights into Canada's S&T capacity (CCA, 2006). However, there is also the risk that responses to these types of surveys may be skewed by any number of biases.[7] Some of these biases can be controlled for — for example, in analyzing the international survey data for this study the results were weighted by country of respondent to eliminate the potential bias from an overrepresentation of responses from any one country or region. However,

7 Common types of bias associated with opinion surveys include self-selection bias (i.e., respondent population is skewed towards those with a predisposition to participate); and biases associated with survey design and question order.

other sources of bias are more subtle. There may not always be a common understanding of how a particular research field is defined, or respondents may provide assessments of Canada's capacity based on anecdotal evidence or unique experiences with particular research establishments or collaborators. There is always the possibility that responses to questions about Canada's research standing are grounded primarily on the impressions of respondents (which may be more or less reliable) rather than by precise knowledge.

There are also specific limitations related to the number of respondents for the opinion surveys in this report. Although there were over 5,000 responses to the international survey, not all fields were equally covered and responses for some fields were low. This was especially true for fields in the arts and humanities. As a result, data for these fields should be interpreted with caution. The Canadian survey had a comparatively lower number of respondents and therefore this limitation is also relevant to many of the fields and sub-fields from that survey.

Finally, one other significant limitation of the Canadian survey is that, due to the change in sampling protocol, the results of this survey are not entirely comparable with those from 2006. For the 2006 assessment, an open sample design was used and there were no limitations on who could respond to the survey. However, with the current survey, to help control for the risk of self-selection, the survey was distributed to a pre-selected group of respondents. While this step makes the survey more rigorous and reliable in general, the change in the sampling approach means that the results are not directly comparable to 2006, a limitation that should be kept in mind when inferring any trends based on comparisons of the data from the two studies.

2.2.4 Research Capacity — Analysis of Highly Qualified and Skilled Personnel

The Panel recognized the importance of analyzing factors related to Canada's *capacity* for conducting world-leading scientific research and technology development, including research infrastructure and facilities, trends in Canada's research faculty and student populations, the degree of collaboration among researchers in Canada and other countries, and researcher migration between Canada and other countries. These types of analyses were not performed in 2006, but have been undertaken in comparable reports internationally (e.g., BIS, 2011).

The Panel drew evidence from a variety of sources for these analyses. In some cases, bibliometric data were used: for example, data on the co-authorship of papers were analyzed to assess research collaboration trends, and data on changes in the institutional affiliation of researchers in bibliometric databases over time were used to analyze researcher migration between Canada and other countries. In other cases, the Panel analyzed existing information and statistics from sources such as the OECD and Statistics Canada. Data on student training and research faculty in Canada were drawn from Statistics Canada's Postsecondary Student Information System (PSIS) and the University and College Academic Staff System (UCASS) survey. This allowed the Panel to analyze both teachers and researchers in Canada, and graduates from Canadian post-secondary educational institutions, by field of study. Data from all of these sources were used to analyze the determinants of research capacity at both a national and provincial (or regional) level. The findings are reported in Chapters 8 and 9, and data tables can be found in Appendix 8.

The benchmark for international comparisons of HQ&SP varies by type of analysis but is typically OECD countries.

Limitations of the Analysis of Highly Qualified and Skilled Personnel

The analysis of highly qualified and skilled personnel presented in this study is based primarily on Statistics Canada data sources. These sources may not always be comparable to those used in other countries or those stemming from OECD data. For a description of the general accuracy and limitations of these data sources, see Statistics Canada (2011a, 2012b). In addition, for this study Statistics Canada data were re-coded in order to match the Science-Metrix discipline ontology used for the rest of the study. Such coding inevitably relies on individual judgment with respect to particular assignments. The complete mapping of Statistics Canada discipline classifications to those used in this study is presented in Appendix 8.

2.3 S&T'S CONTRIBUTION TO SOCIAL AND ECONOMIC OBJECTIVES

The methodologies used in this report have many strengths. In terms of the definition of S&T strength (see Box 1.1), the methodologies taken together allow for an assessment of the quality of S&T, the magnitude of S&T, and the trends in those factors. They do not, however, allow an assessment of the last element in the definition "the extent to which our S&T capabilities can be applied effectively to achieve social and economic objectives" (CCA, 2006) — the societal impact of Canadian S&T. In almost all fields of S&T there is an aim, at some level, to have a policy, social, or economic impact. None of the research methods employed by the Panel directly analyze these types of research impacts. This is particularly problematic for certain fields in the social sciences where research may often be directly focused on informing public policy or improving community services.

While there are methodologies that can be used to assess these types of impacts (e.g., CAHS, 2009), none were feasible in the context of the Panel's work, which focused on evidence to support international comparisons of research performance across fields. A comprehensive and internationally comparable study of this type of impact for even one field would be an enormous undertaking. Although the Panel recognized the value of this type of analysis, studies across all fields of research were beyond its resources.

2.4 MEASURING RESEARCH IN THE HUMANITIES, ARTS, AND SOCIAL SCIENCES

The Panel took very seriously feedback that the 2006 S&T report had not adequately considered the unique circumstances of research in the humanities, arts, and social sciences (HASS), particularly those that make bibliometric measures less appropriate. Although peer-reviewed articles are the primary means of disseminating new knowledge in the natural sciences, health sciences, and engineering, this is not the case in the HASS, where books and book chapters (which are not included in the bibliometric database) are a common, and often more prestigious, means of disseminating knowledge. As a result, bibliometrics is an imperfect measure of strength in these areas (though to some extent, advances in bibliometric research and improvements to the databases, mean that social science research in particular is not as poorly served as it was in the past).

A further complicating factor for the analysis of bibliometric data in HASS fields is the limited coverage of Canadian journals. While researchers in other fields usually choose the best possible journal worldwide in which to publish their research, HASS scholars often preferentially choose Canadian journals because of the relevance of the research to local conditions. For example, in fields such as Canadian history, much of the discussion is particular to Canada and of limited interest to international audiences. Of the approximately 170 scholarly journals supported by the Social Sciences and Humanities Research Council's (SSHRC) Aid to Scholarly Journals program, only 70 are captured in the Scopus database used for the bibliometric analysis in this assessment. Although this is higher than for the other major database, the Web of Science, it still means that articles in over half of these Canadian journals are not accounted for in the bibliometric analysis.

An analysis of the missing journals highlights an additional problem: French-language Canadian journals are noticeably absent from the Scopus database. This is less of a problem for natural and health sciences and engineering, where English tends to be the international language of communication. In HASS fields, however, scholars in Canada may choose to publish in French, but bibliometric databases are generally biased towards English language publications. On the other hand, this bias may favour Canadian HASS research in bibliometric terms when compared with countries in which English is not an official language.

Bibliometric measures are even less suited to capturing strength in the visual and performing arts. For many arts or design researchers, validation of results occurs through the circulation and take-up of the resulting practice, through exhibitions, performances, applications of designs, or digital media works or software. This fact is now widely recognized by both Canadian and international organizations involved in research evaluation related to the arts. For example, the Bologna Process in Europe, which established quality assurance and subsequent national research evaluation exercises (Kubikowski, 2011), recognized practice and its circulation as part of research excellence, as does SSHRC, which also recognizes "any research activity or approach to research that forms an essential part of a creative process or artistic discipline and that directly fosters the creation of literary/artistic works" (Archambault *et al.*, 2007). As well in Canadian and international universities, tenure and ranking decisions are based on creative outputs as well as publications in the evaluation of faculty performance.

Another issue with respect to the arts is what constitutes a desired venue for publication. Although researchers may choose to publish research results in peer-reviewed journals or books, one of the characteristics of contemporary art, design, and digital media practice is the drive to create new categories, practices, and venues for circulation. For example, there is a tension between a peer context, which values the creation of dynamic and responsive online publication venues, and that of bibliometric practices, which may discount such venues in favour of longevity and stability. There are also few academic associations for design or fine and performing arts and digital media that legislate a hierarchy of publication venues. The result is that bibliometrics, while retaining validity, is capable of capturing only a small fraction of the full range of activities and outputs that should be taken into account for these fields.

While the Panel believes that most other evidence-gathering activities undertaken for this assessment are equally valid across all fields, the limitations of bibliometrics led the Panel to seek measures of the impact of HASS research that would be equivalent to the use of bibliometrics, and would measure knowledge dissemination by books, book chapters, international awards, exhibitions, and other arts productions (e.g., theatre, cinema, etc.). Despite considerable efforts to collect information, however, the Panel found the data to be sparse and methods to collect it unreliable, such that it was not possible to draw conclusions from the resulting data. In short, the available data for HASS-specific outputs did not match the quality and rigour of the other evidence collected for this report. As a result, this evidence was not used in the Panel's deliberations.

Despite the limitations of bibliometrics with respect to HASS fields, the Panel has used the bibliometric evidence that is available, together with the survey and other data, to draw conclusions about strengths in these disciplines.

2.5 CONCLUSIONS

The multi-lens methodology used in this report provides a detailed and comprehensive approach to assessing the magnitude, quality, and trends of S&T in Canada compared with other advanced countries. Each lens used in the report brings strengths and limitations, and some may be more effective at measuring strength in certain fields. Taken together, however, the approaches used in this report provide one of the most comprehensive assessments of Canadian S&T ever undertaken.

3

Research Investment

- Overview of Research Expenditures in Canada
- Recent Trends in Research Expenditures in Canada
- Federal Expenditures on R&D
- Conclusions

3 Research Investment

This report is concerned first and foremost with assessing Canada's S&T strengths. International comparisons of investment levels are not, in and of themselves, a measure of strength, however S&T strength does not develop without ongoing investment. While S&T and R&D are not synonymous (S&T being a broader concept), this Chapter reports "R&D" expenditures as these are the most widely used basis for international comparisons (see Box 3.1) and for the purposes of this chapter are used as a proxy for S&T expenditures. Therefore, to provide context for the remainder of the report, this chapter highlights the major trends related to Canada's overall investment in R&D. These data are periodically reviewed in a number of sources including various Statistics Canada publications (e.g., Statistics Canada, 2012a); Organisation for Economic Co-operation and Development (OECD) publications (e.g., OECD, 2011a); and the biennial state of the nation reports produced by Canada's Science, Technology and Innovation Council (STIC) (STIC, 2009; 2011).

Box 3.1
Definitions of R&D Expenditure Indicators

The Panel used OECD and Statistics Canada data on R&D expenditures in Canada and abroad:

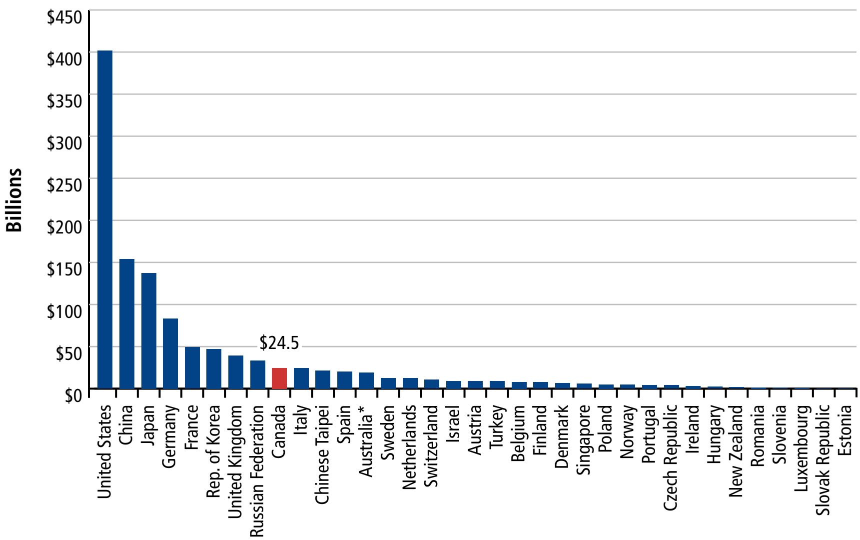
- Total countrywide R&D investment is captured by gross domestic expenditure on research and development (GERD).
- R&D that is performed within the private sector is referred to as business enterprise expenditure on research and development (BERD).
- R&D that is performed within the higher education sector is referred to as higher education expenditure on research and development (HERD).

(OECD, 2011a)

BERD and HERD refer to R&D *performed* in those sectors, rather than *funded by* those sectors. For example, funding for HERD comes from several sources, including government, business, and the higher education sector itself. These statistics are collected and reported based on OECD definitions and guidelines as published in the Frascati Manual (OECD, 2002).

3.1 OVERVIEW OF RESEARCH EXPENDITURES IN CANADA

Canada's overall level of investment in R&D today has declined compared to the level reported in the Council's 2006 report, *The State of Science and Technology in Canada*. As shown in Figure 3.1, when viewed in absolute terms, Canada ranks ninth in the world in terms of total gross domestic expenditures on R&D (GERD).



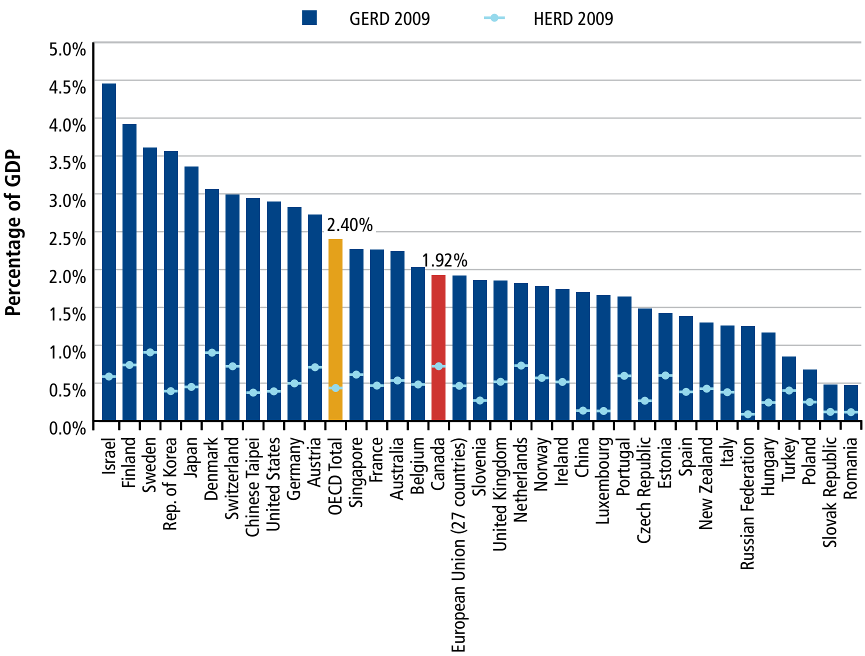
Notes: *Data for 2008;
Dollar amounts are adjusted for purchasing power parity (PPP)
Data source: OECD (2010). *Main Science and Technology Indicators*

Figure 3.1
Gross Domestic Expenditure on R&D (GERD) (millions of current PPP $), 2009

However, when R&D spending is expressed as a percentage of gross domestic product (GDP) (see Figure 3.2), Canada's level of investment in R&D is below the OECD average,[8] and well below the level of investment in R&D in countries such as Israel, Finland, and Sweden (all of which invest in excess of 3.5 per cent of their GDP in support of R&D). Canada's R&D expenditures relative to GDP, however, are above the European Union 27 country average, above several countries with populations larger than Canada, and above some leading S&T performers, such as the United Kingdom. Canadian R&D expenditures are not evenly distributed

8 Defence R&D accounts for a large proportion of GERD in many countries. This is not the case in Canada.

across the country, with almost half of all expenditures in Ontario, and 92 per cent of all spending accounted for by four provinces — Ontario, Quebec, British Columbia, and Alberta. Provincial differences are explored in Chapter 9.



Note: HERD=higher education expenditure on R&D
Data source: OECD (2010). *Main Science and Technology Indicators*

Figure 3.2
Gross Domestic Expenditure on R&D (GERD) in Selected Countries as a Percentage of GDP, 2009

One of the most distinctive features of Canadian R&D spending relative to other countries is that it is more concentrated in the higher education sector. Canada, like Nordic countries, Israel, and the Netherlands, exhibits substantial higher education expenditure on R&D (HERD) (see Figure 3.2). This accounted for approximately 38 per cent of all R&D in Canada in 2009 (Statistics Canada, 2012a). In comparison, the higher education sector accounts for only 18 per cent of total R&D in the average OECD country and 14 per cent in the United States (OECD, 2010).

The corollary is that a relatively low share of Canadian R&D investment occurs in the business sector. In 2009, 52 per cent of Canadian R&D was performed by business enterprises. In contrast, in the OECD on average, 67 per cent of R&D is performed in the business enterprise sector. These trends in Canadian R&D performance have been widely discussed in recent years (STIC, 2009, 2011; CCA, 2009; Industry Canada, 2011b).

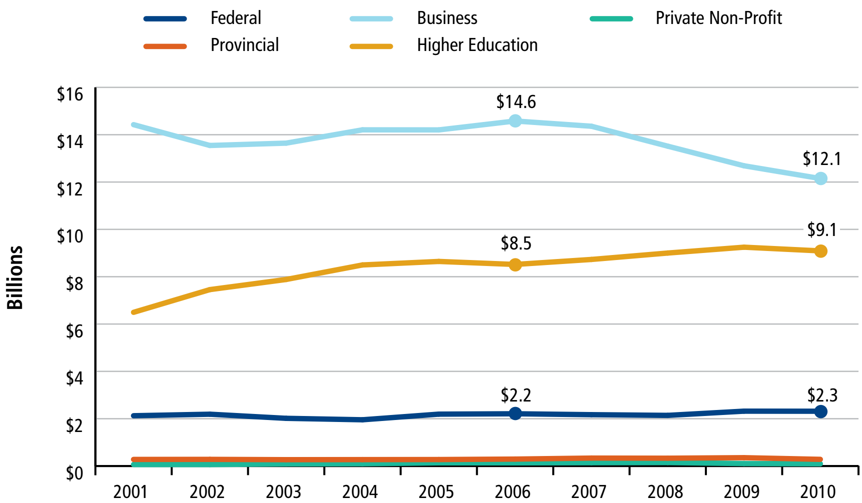
The share of Canadian R&D performed by business declined in the period 2006–2009, almost to 50 per cent in 2009. Since countries with a share below 50 per cent tend to be small or developing economies, crossing that boundary is a concern for Canada. Preliminary estimates, however, show that the business share of Canada's R&D performance increased in 2011 (Statistics Canada, 2012a).

Canada's comparatively low level of private-sector investment in S&T has been identified as a primary cause of Canada's lagging productivity growth in relation to many other countries (particularly the United States). For example, the Council of Canadian Academies' assessment on innovation and business strategy explored this subject and its implications for Canadian productivity in detail (CCA, 2009).

3.2 RECENT TRENDS IN RESEARCH EXPENDITURES IN CANADA

A closer look at recent R&D expenditure trends shows that Canada's total investment in R&D has declined in real terms between 2006 and 2010, driven mainly by declining private-sector research performance. Both government and higher education R&D expenditures increased modestly over the same five-year period (growing by 4.5 per cent and 7.1 per cent respectively), while business R&D declined by 17 per cent (see Figure 3.3). Much of this decline can be attributed to the failing fortunes and bankruptcy of Nortel Networks Corporation, which was one of Canada's top corporate R&D spenders for many years. Between 2008 and 2009 alone, global R&D expenditure at Nortel dropped by 48 per cent, from nearly $1.7 billion to approximately $865 million (Re$earch Infosource, 2010) with significant impact on Canada. Although growth in R&D expenditure at other Canadian companies, particularly Research In Motion, partially compensated for the decline at Nortel, the overall downward trend remains.

Canada is the only OECD country with a net decline (of over six per cent) in R&D expenditures between 2005 and 2010 (see Figure 3.4). Japan and the Netherlands also had declining R&D expenditures in individual years during this five-year period. In contrast, total R&D spending increased by 17.4 per cent on average in real terms over the same period in the OECD. This, however, is modest in comparison with the records of growth shown by countries such as China in the same period. Total R&D expenditures more than doubled in China, which had an annual growth rate of around 19 per cent.

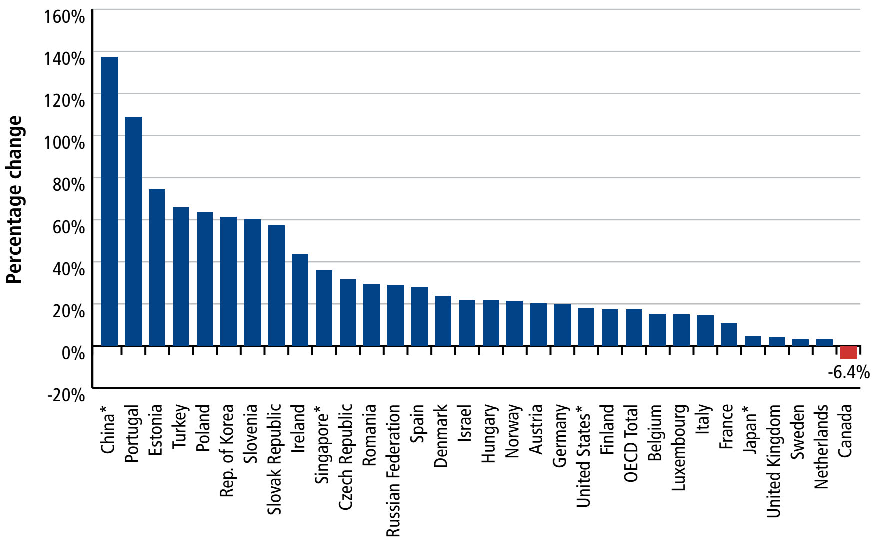


Data source: Statistics Canada (2012a). *Gross Domestic Expenditures on Research and Development in Canada (GERD), and the Provinces*

Figure 3.3
R&D Expenditures by Performing Sector in Canada, 2001–2010 (Constant 2002 Dollars)

Figures 3.5 and 3.6 both show trends in the growth of R&D spending in the business sector and in the higher education sector during the same period. These figures clearly illustrate that declining R&D activity in the private sector is the primary source for Canada's overall negative trend. Growth in higher education expenditure on R&D was modestly positive over the period 2005–2010, though still low by international standards. Growth in private-sector R&D in Canada, however, was negative — the lowest of all countries for which the OECD has data.

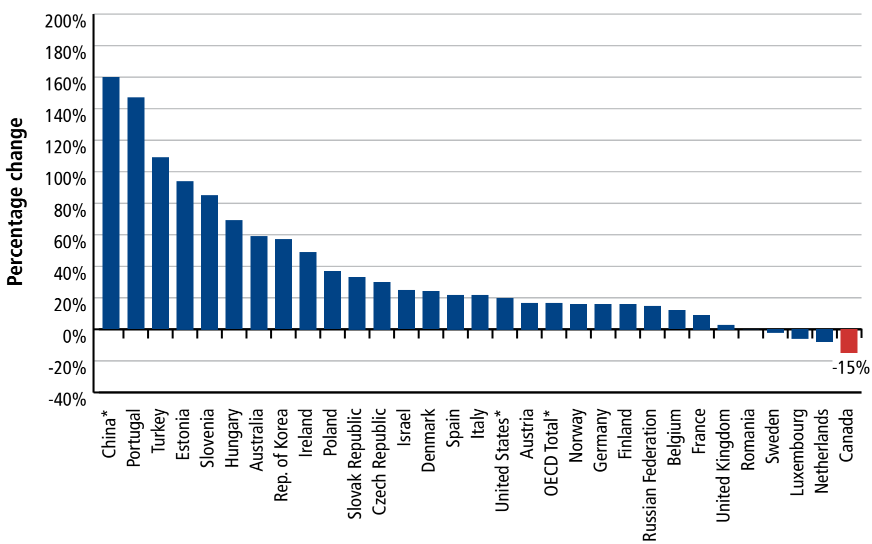
While the amount of R&D performed in the private sector is comparatively low in Canada, businesses fund a significant amount of R&D that is actually performed in the higher education sector. Figure 3.7 shows the percentage of R&D spending in the higher education sector financed by industry. In Canada, industry funds just over eight per cent of all R&D performed in the higher education sector (approximately $950 million in 2011) (Statistics Canada, 2012a). This is above average for OECD countries, and is more than double the percentage of HERD financed by industry in the United Kingdom, Norway, Denmark, Japan, France, and Italy.



Notes: Based on constant 2005 dollars and PPP; * indicates change between 2004 and 2009
Data source: OECD (2010). *Main Science and Technology Indicators*

Figure 3.4

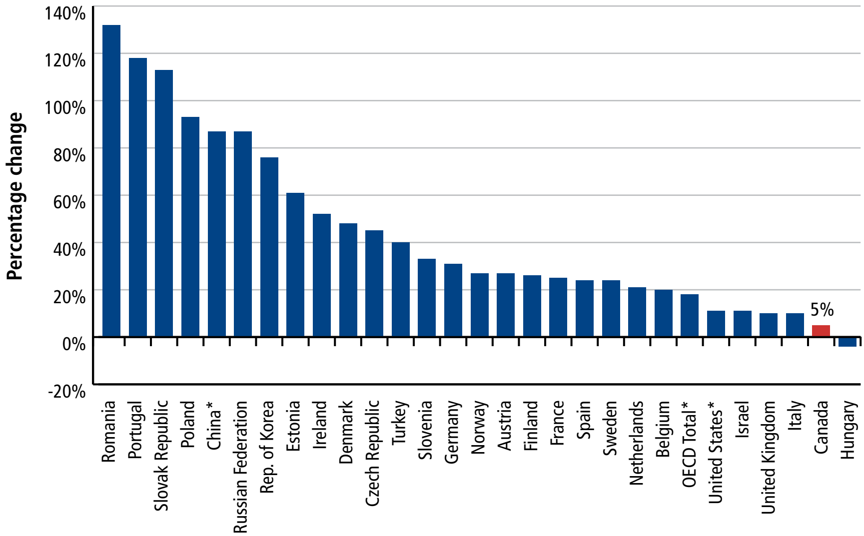
Percentage Change in GERD for Selected Countries, 2005–2010



Notes: Based on constant 2005 dollars and PPP; * indicates change between 2004 and 2009
Data source: OECD (2010). *Main Science and Technology Indicators*

Figure 3.5

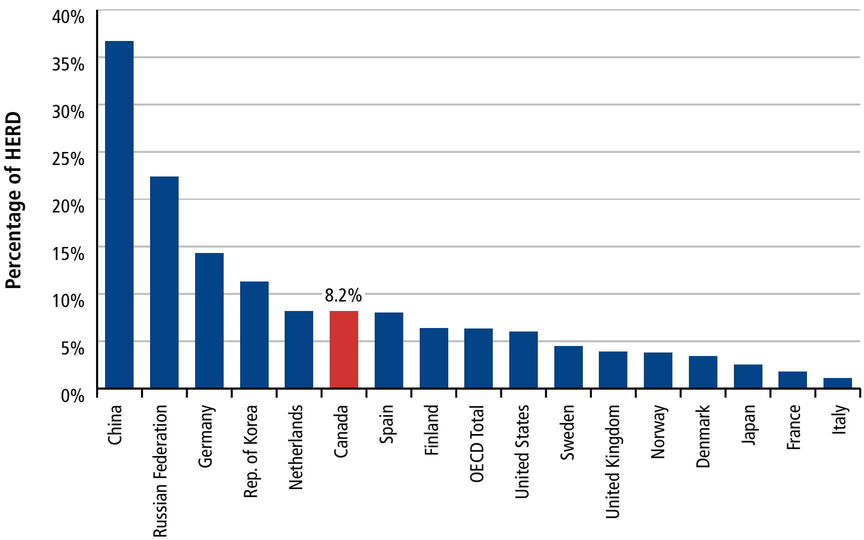
Percentage Change in BERD for Selected Countries, 2005–2010



Notes: Based on constant 2005 dollars and PPP; * indicates change between 2004 and 2009
Data source: OECD (2010). *Main Science and Technology Indicators*

Figure 3.6

Percentage Change in HERD for Selected Countries, 2005–2010



Data source: OECD (2010). *Main Science and Technology Indicators*

Figure 3.7

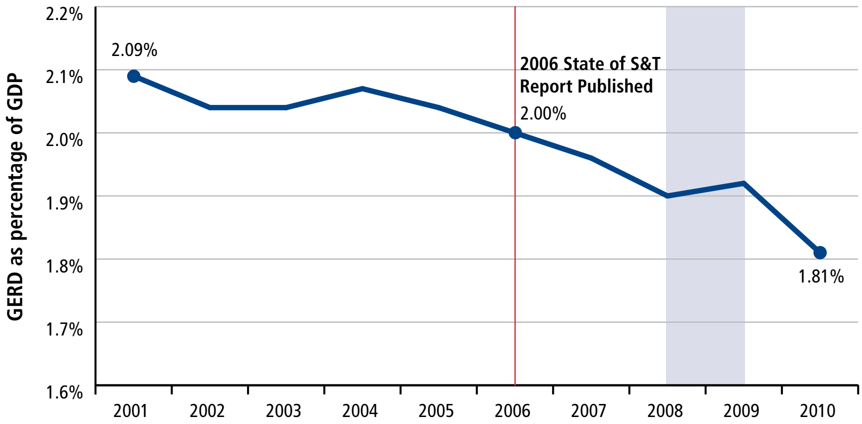
Percentage of HERD Financed by Industry, 2009

3.3 FEDERAL EXPENDITURES ON R&D

Federal support for R&D in Canada has continued to grow in recent years, increasing from approximately $5.4 billion in 2004 to a projected $7.6 billion in 2010/2011 (Statistics Canada, 2011e), and for the entire S&T enterprise federal expenditures are projected to be $11.9 billion in the year 2010/2011 (Statistics Canada, 2011e), not including the Scientific Research and Experimental Development (SR&ED) tax credit. Federal R&D expenditures are divided roughly equally between support for intramural (within government) R&D and extramural (outside of government) R&D. The major federal agencies that support extramural R&D are the Canadian Institutes of Health Research (CIHR), the Natural Sciences and Engineering Research Council of Canada (NSERC), the Social Sciences and Humanities Research Council of Canada (SSHRC), the Canada Foundation for Innovation (CFI), and the National Research Council Canada (NRC). In terms of the socio-economic focus of federal expenditure, by far the largest amount of investment goes towards research aimed at improving and protecting human health.

3.4 CONCLUSIONS

Canada's level of R&D investment is lower than the OECD average, but on par with comparable economies such as the United Kingdom, the Netherlands, and France. Similar to the Nordic countries, Israel, and the Netherlands, Canada invests substantially in R&D in the higher education sector. Levels of investment in business R&D are low compared with other OECD countries. Canada's level of R&D investment, as expressed as a share of GDP, has decreased since the Council's 2006 S&T report (see Figure 3.8) with the only growth in this indicator occurring during the 2008 recession, when GDP growth (the denominator) was negative. While the overall breakdown of R&D investment in Canada, and Canada's relative international standing, remains similar to 2006, Canada is unique among all OECD countries in its net decline in total R&D spending in the past six years, caused by large declines in business expenditures on R&D, with Nortel's bankruptcy likely playing a major role.



Data source: Statistics Canada (2012a). *Gross Domestic Expenditures on Research and Development in Canada (GERD), and the Provinces*

Figure 3.8

GERD as Percentage of GDP in Canada, 2001–2010

This figure shows the evolution of gross domestic expenditure on R&D (GERD) compared to GDP over the past decade in Canada. The area marked in light blue shows the recession between 2008 and 2009 — the only time during the period shown that Canadian GDP dropped.

4

Research Productivity and Impact

- Canada's Research Output
- Canada's Research Impact
- Synthesizing Research Output and Impact
- Comparison with the 2006 Report
- Conclusions

4 Research Productivity and Impact

Key Findings

- Canada has less than 0.5 per cent of the world's population, yet accounted for 4.7 per cent of the world's one per cent most highly cited papers between 2000 and 2008.
- Canada ranks sixth among major scientific countries in terms of average levels of citation across all fields — a measure of research impact.
- Canadian research is particularly highly cited relative to world averages in the fields of Visual and Performing Arts, Clinical Medicine, and Physics and Astronomy.
- Canadian research ranks first in the world in nine sub-fields, and in the top 10 in the world in nearly all sub-fields by levels of citation.
- Canada ranks seventh in the world in total production of research papers — a measure of research output.
- Canada's share of the world's scientific publications is particularly high in the fields of Psychology and Cognitive Sciences; Public Health and Health Services; Philosophy and Theology; Earth and Environmental Sciences; and Agriculture, Fisheries, and Forestry.

Many countries periodically assess their scientific activity based — at least in part — on bibliometric data (see Chapter 2). Canada is no exception. The first report by the Council, *The State of Science and Technology in Canada*, used bibliometric analysis to gauge Canada's scientific performance relative to other countries (CCA, 2006). This type of evidence provides a valuable way to assess both the volume of scientific output in terms of numbers of papers and the impact of a nation's scientific research in terms of citations. This Panel has built on the 2006 analysis by providing a comprehensive review of data and indicators based on Canada's output of scientific papers using a similar — though expanded — set of bibliometric indicators (see Box 4.1 for a description of bibliometric indicators).

This chapter provides the results of this aspect of the Panel's research. The chapter is organized as follows:

- **Section 4.1** reviews evidence on the overall *output* of research papers in Canada in comparison to the rest of the world.
- **Section 4.2** provides evidence on the *impact* of Canada's research publications, as captured by citations.
- **Section 4.3** then offers a *synthesis* of indicators relating to both output and impact on a field-by-field basis.

Box 4.1
Bibliometric Indicators Used in this Study

Publication Counts: Publication counts correspond to the total number of peer-reviewed journal articles published by a field or sub-field of research. These may be "whole" counts, where every author receives full credit for a publication, or "fractional" counts, where every author receives a fractional credit based on the total number of authors for the article. (The publication counts presented in this chapter are based on whole counts unless otherwise noted.)

Specialization Index (SI): This indicator is a measure of Canada's concentration of research activity in particular research fields relative to other countries. An SI score greater than 1.0 indicates that more articles are published in that field or sub-field than would be expected based on world averages.

Average Relative Citations (ARC): ARC is a measure of the frequency of citation of publications. An ARC score greater than 1.0 indicates that publications are more highly cited than the world average for that field or sub-field of research (all ARC scores are normalized by field of research). ARC scores are generally more reliable and robust when based on a larger number of papers; thus fields with small numbers of papers may show more volatility in these scores. For this study, no ARC scores are computed for any field or sub-field with less than 30 papers.

Growth Index (GI): Publication growth can be calculated based on either whole counts of publications or fractional publication counts. In this report, the Growth Index is calculated based on the gross rate of growth of whole counts of publications between two periods of time (e.g. the number of papers published between 2005 and 2010 divided by the number of papers published between 1999 and 2004). A GI score above one indicates a growing field, while a GI score below one indicates a field with declining publication output.

For a more detailed explanation of methods used in calculating each of these indicators, see Appendix 1.

4.1 CANADA'S RESEARCH OUTPUT

In many fields of S&T the peer-reviewed journal article is the principal method of communicating research advances throughout the world. Peer review is a form of quality control, meaning that other experts in the field believe that the article has merit. Therefore the numbers of journal articles can be used as an international comparison of the magnitude of S&T.[9]

9 See Chapter 2 for a discussion of the limitations of bibliometrics.

4.1.1 Overall Research Output

Canada ranked seventh in the world in total output of scientific papers in 2005–2010 (see Table 4.1), producing roughly 395,000 scientific and academic articles, which accounted for 4.1 per cent of the world's total output (high, compared to having 0.5 per cent of the world's population). Canada has maintained its overall standing in terms of research output over the last decade — despite earlier concerns that it was likely to be overtaken by countries in Asia with rapidly growing scientific establishments (e.g., Archambault & Gingras, 2004). Canada's rank among these countries remained unchanged between the two periods (1999–2004 and 2005–2010)

Table 4.1

Top 20 Countries by Number of Scientific Papers Produced

		Number of Papers		Share of World Papers (%)	
Rank 2005–2010	Country	2005–2010	1999–2004	2005–2010	1999–2004
1	United States	2,559,751	1,924,095	26.7	30.9
2	China	1,589,748	486,934	16.6	7.8
3	United Kingdom	688,990	503,210	7.2	8.1
4	Germany	648,542	482,678	6.8	7.7
5	Japan	647,867	550,328	6.8	8.8
6	France	479,452	350,900	5.0	5.6
7	Canada	395,369	248,756	4.1	4.0
8	Italy	369,398	247,835	3.9	4.0
9	Spain	306,505	178,616	3.2	2.9
10	India	293,656	150,732	3.1	2.4
11	Australia	267,938	160,243	2.8	2.6
12	Rep. of Korea	265,146	124,789	2.8	2.0
13	Netherlands	210,153	140,778	2.2	2.3
14	Brazil	203,604	92,499	2.1	1.5
15	Russia	200,176	172,448	2.1	2.8
16	Switzerland	152,122	100,533	1.6	1.6
17	Poland	141,005	89,829	1.5	1.4
18	Turkey	138,881	64,061	1.4	1.0
19	Sweden	138,353	106,477	1.4	1.7
20	Belgium	117,174	76,663	1.2	1.2
	World	9,586,347	6,230,213	100.0	100.0

Data source: Calculated by Science-Metrix using Scopus database (Elsevier)

The number of papers is expressed here in whole counts, which allot full credit to every author listed on a paper. As a result, growth in paper output here is partially driven by increasing research collaboration (see Chapter 6). When changes in collaboration rates are factored in, Canada's growth in paper output is just below the world average.

as growth in Canada's output of scientific papers has been roughly on par with the world average of 54 per cent. Canada's share of world publications actually increased between the two periods, growing by nearly 60 per cent, the only G7 country to increase its share of world papers. This fact is impressive given the dramatic increase in scientific paper output from China over the past decade, resulting in its share of publications increasing from 8 per cent to over 16 per cent from the years 1999–2004 to 2005–2010.

4.1.2 Research Output by Field

Canada's output of scientific papers varies considerably by field[10] of research (see Table 4.2). The largest research fields in terms of absolute counts of papers are Clinical Medicine,[11] ICT, and Engineering. These fields also account for the bulk of scientific papers in many other countries. A more revealing indicator is Canada's overall share of world papers in each field of research (shown for the periods 2005–2010 and 1999–2004 in the table). At the top end of the scale, Canadians produced 7.6 per cent of the world's papers in Psychology and Cognitive Sciences in 2005–2010. At the other end of the scale, Canadians accounted for only 2.6 per cent of the world's output of scientific journal articles in Chemistry in the same period. (The low output in fields such as Chemistry and Physics could possibly be explained by researchers in those fields publishing in journals captured elsewhere in the classification system; for example, a chemist's or physicist's article in a nanotechnology journal would likely be captured in the field of Enabling and Strategic Technologies, but — for this particular example and others — this does not appear to be the case. Given the relatively low output across all of Chemistry, Physics, and Enabling and Strategic Technologies, it is more likely that Canada performs less research than average in these fields.) Canada's share of the world's papers increased in 10 fields, declined in 5, and remained stable in 7, compared to the preceding five-year period (see Table 4.2).

The final two columns in Table 4.2 show the Specialization Index (SI), a measure of the overall level of research activity in a particular field relative to the rest of the world. It is constructed by comparing Canada's article output in a field (as a percentage of Canada's total output) with the world's article output in the same field (as a percentage of the world's total output). If Canada produces more papers in a field than would be expected based on world averages, the SI is greater than 1.0. If it produces fewer papers, the SI is less than 1.0.

10 See Section 2.1 for an explanation of the field and sub-field classification used in this report. This section also explains that Clinical Medicine is broader than in some common usages.

11 *ibid.*

Table 4.2

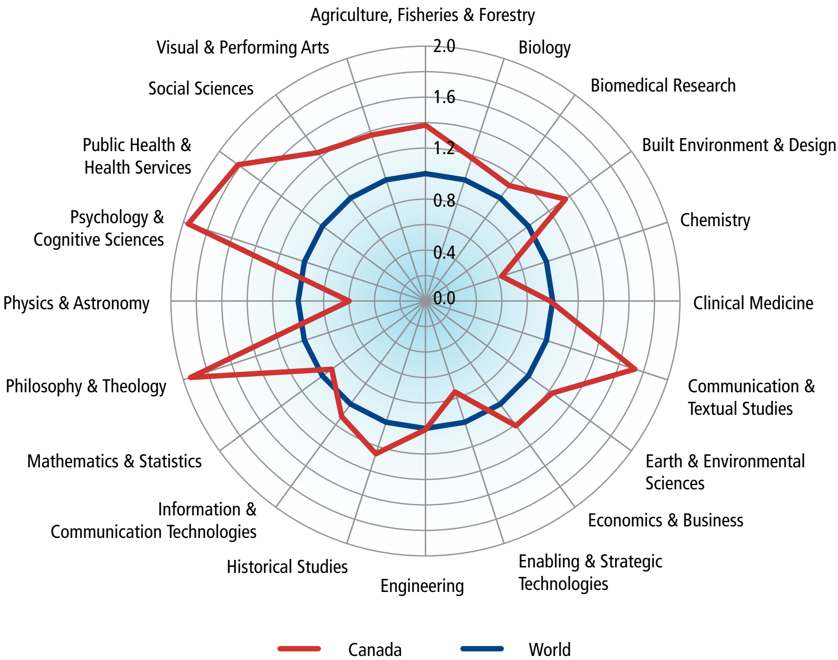
Total Paper Output, Share of World Papers, and Specialization Index by Bibliometric Field of Research in Canada

Field	Number of Papers 2005–2010		Canada's Share of World Papers (%)		Specialization Index (SI)	
	Canada	World	2005–2010	1999–2004	2005–2010	1999–2004
Clinical Medicine	88,354	2,159,622	4.09	3.69	0.98	0.94
Information & Communication Technologies	40,529	931,001	4.35	5.06	1.12	1.32
Engineering	34,927	891,620	3.92	4.39	1.01	1.17
Biomedical Research	31,326	631,678	4.96	4.60	1.12	1.09
Physics & Astronomy	30,890	1,018,777	3.03	2.69	0.60	0.55
Enabling & Strategic Technologies	26,896	908,140	2.96	2.65	0.75	0.69
Biology	18,227	348,408	5.23	5.31	1.18	1.29
Chemistry	17,653	690,586	2.56	2.60	0.63	0.66
Agriculture, Fisheries & Forestry	15,880	297,996	5.33	6.31	1.38	1.69
Earth & Environmental Sciences	15,788	272,605	5.79	5.63	1.23	1.3
Public Health & Health Services	15,298	222,273	6.88	6.10	1.82	1.64
Social Sciences	12,355	263,467	4.69	4.51	1.44	1.39
Psychology & Cognitive Sciences	12,319	161,220	7.64	7.12	1.96	1.93
Economics & Business	10,161	211,904	4.80	5.03	1.21	1.33
Mathematics & Statistics	8,951	213,955	4.18	4.11	0.91	0.92
General Science & Technology	3,775	121,075	3.12	3.31	0.54	0.65
Historical Studies	3,512	73,752	4.76	4.55	1.26	1.22
Built Environment & Design	3,152	63,750	4.94	5.75	1.36	1.62
Communication & Textual Studies	2,686	52,085	5.16	5.07	1.73	1.76
Philosophy & Theology	2,024	34,295	5.90	5.17	1.94	1.74
General Arts, Humanities & Social Sciences	380	10,438	3.64	3.36	1.14	1.08
Visual & Performing Arts	286	7,700	3.71	2.67	1.37	1.10
Total	**395,369**	**9,586,347**	**4.12**	**3.99**	–	–

Data source: Calculated by Science-Metrix using Scopus database (Elsevier)

In this table the number of papers is expressed in whole counts and fields are ranked by the order of the number of papers from Canada from highest to lowest. The fields are coloured according to whether Canada's share of world publications has grown or declined. Green = fields where Canada's share of world publications has grown. Red = fields where Canada's share of world publications is declining. Yellow = fields where Canada's overall share has been relatively stable (increasing or decreasing by less than 0.2 per cent).

Figure 4.1 displays the SI scores by field of research for Canada between 2005 and 2010. Compared to the world average, Canada has a relatively high concentration of research activity in several fields, particularly Philosophy and Theology, Psychology and Cognitive Sciences, Public Health and Health Services, and Communication and Textual Studies. In comparison, Canada has relatively low concentrations of activity in Chemistry, Enabling and Strategic Technologies, Physics and Astronomy, and Mathematics and Statistics.



Data source: Calculated by Science-Metrix using Scopus database (Elsevier)

Figure 4.1

Specialization Index (SI) by Field of Research in Canada, 2005–2010

This figure shows the SI scores by field of research, which indicate whether Canada publishes more or less research in a given field than would be expected based on the world average.

As shown in Table 4.2, over the past 10 years Canada's level of specialization has decreased substantially in Agriculture, Fisheries, and Forestry (although it remains above the world average), and increased significantly in Public Health and Health Services and in Visual and Performing Arts.

4.1.3 Research Output by Sub-Field

For the vast majority of sub-fields, there are sufficient bibliometric data to compare Canada's international performance at the sub-field level. Table 4.3 shows the top quartile of research sub-fields (44 of 176 sub-fields) in Canada by share of world papers and SI score. These sub-fields are all areas where Canada accounts for a relatively large share of the world's journal articles. Many areas of research related to natural resources figure strongly here, including Geology, Forestry, and Fisheries. Canada also has a high level of research activity in Automobile Design and Engineering, and in several sub-fields related to psychology and mental health, including Experimental Psychology, Behavioural Science, Developmental and Child Psychology, Clinical Psychology, and Social Psychology.

Table 4.3

Top Quartile of Sub-Fields in Canada by Share of World Papers and Specialization Index (SI)

Sub-Field	Field	Canada's Share of World Papers (2005–2010) (%)	SI
Geology	Earth & Environmental Sciences	10.45	2.37
Forestry	Agriculture, Fisheries & Forestry	10.40	2.96
Physiology	Biomedical Research	9.59	2.37
Ornithology	Biology	8.80	1.93
Experimental Psychology	Psychology & Cognitive Sciences	8.78	2.13
Fisheries	Agriculture, Fisheries & Forestry	8.59	2.03
Automobile Design & Engineering	Engineering	8.37	2.30
Rehabilitation	Public Health & Health Services	8.34	2.33
Behavioural Science & Comparative Psychology	Psychology & Cognitive Sciences	8.29	2.07
Health Policy & Services	Public Health & Health Services	8.15	1.97
Medical Informatics	Information & Communication Technologies	8.06	2.21
Sport, Leisure & Tourism	Economics & Business	7.88	2.12
Human Factors	Psychology & Cognitive Sciences	7.73	2.06
Gerontology	Public Health & Health Services	7.59	2.08
Developmental & Child Psychology	Psychology & Cognitive Sciences	7.59	2.04
Econometrics	Economics & Business	7.57	1.66

continued on next page

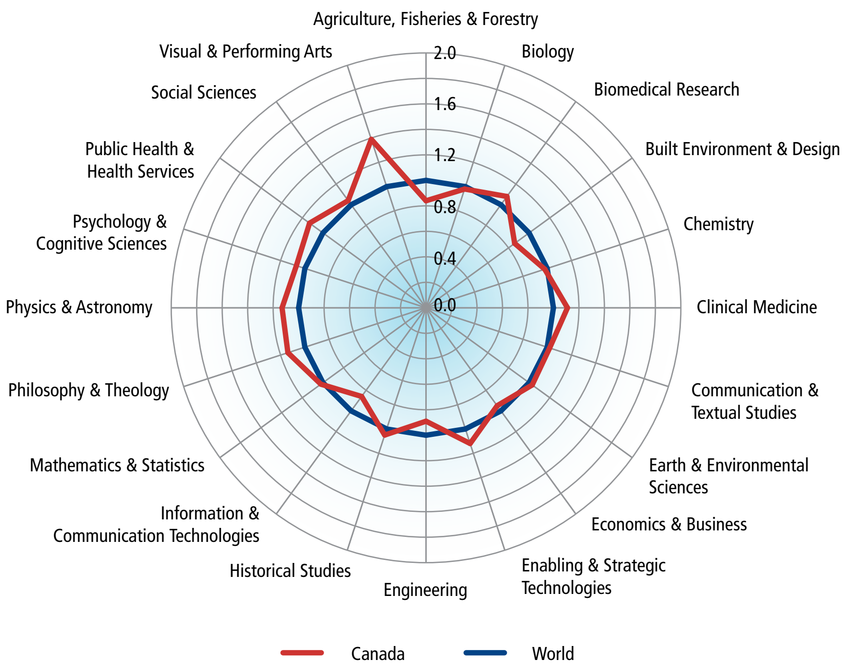
Sub-Field	Field	Canada's Share of World Papers (2005–2010) (%)	SI
Clinical Psychology	Psychology & Cognitive Sciences	7.55	1.94
Sport Sciences	Clinical Medicine	7.53	1.96
Social Psychology	Psychology & Cognitive Sciences	7.52	1.93
Criminology	Social Sciences	7.30	2.17
Ecology	Biology	7.23	1.67
Industrial Relations	Economics & Business	7.10	2.01
Statistics & Probability	Mathematics & Statistics	7.06	1.55
Gender Studies	Social Sciences	7.04	2.19
Computation Theory & Mathematics	Information & Communication Technologies	7.03	1.58
Accounting	Economics & Business	7.01	1.71
Applied Ethics	Philosophy & Theology	7.00	2.15
Epidemiology	Public Health & Health Services	6.97	1.47
Urban & Regional Planning	Built Environment & Design	6.89	1.95
Evolutionary Biology	Biology	6.86	1.43
Geography	Social Sciences	6.84	1.95
Public Health	Public Health & Health Services	6.84	1.77
Literary Studies	Communication & Textual Studies	6.70	2.39
Genetics & Heredity	Biomedical Research	6.66	1.24
Environmental Engineering	Engineering	6.59	1.69
Social Sciences Methods	Social Sciences	6.40	1.76
Meteorology & Atmospheric Sciences	Earth & Environmental Sciences	6.15	1.25
Nursing	Public Health & Health Services	6.00	1.79
Drama & Theater	Visual & Performing Arts	5.92	2.41
Substance Abuse	Public Health & Health Services	5.90	1.52
Software Engineering	Information & Communication Technologies	5.89	1.57
Social Work	Social Sciences	5.88	1.71
Astronomy & Astrophysics	Physics & Astronomy	5.76	0.74
Psychiatry	Clinical Medicine	5.73	1.44

Data source: Calculated by Science-Metrix using Scopus database (Elsevier)

4.1.4 Growth in Canada's Research Output

S&T output changes over time, and for all fields the absolute number of papers increased in 2005–2010 compared with 1999–2004; however, output also increased in other countries. To compare growth rates in Canada's production of scientific papers compared to other countries, a Growth Index (GI) was calculated based on the change in paper output between the periods 1999–2004 and 2005–2010. The GI can be calculated using whole or fractional publication counts; for this report whole counts are used (see Appendix 1 for detailed methodology). A GI score of 1.8, for example, indicates that the output in the period 2005 to 2010 was 180 per cent of output in 1999 to 2004.

Figure 4.2 shows the GI scores for Canada in relation to the world average GI score. The growth in Canadian research in many fields, most notably in Visual and Performing Arts, Public Health and Health Services, Philosophy and Theology, and Physics and Astronomy is impressive given the rapidly growing output in



Data source: Calculated using bibliometric data from Science-Metrix derived from the Scopus database (Elsevier)

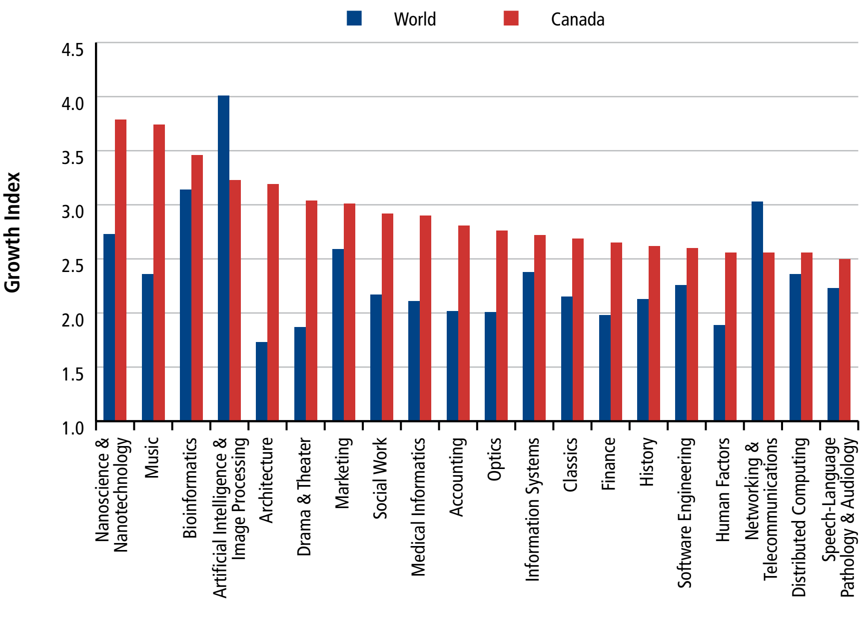
Figure 4.2

Growth Index (GI) by Field of Research for Canada as Compared to the World, 1999–2010

This figure shows the Growth Index (GI) scores for Canada by field of research relative to world GI scores (i.e., Canada's GI score divided by the world GI score for that field of research). The GI score is based on a comparison of whole publication counts between the periods 1999–2004 and 2005–2010.

emerging countries such as China and India. Because of the rapid world growth in S&T it is not surprising that Canada's output in almost half of the fields grew more slowly than total world output, most notably in Agriculture, Fisheries, and Forestry; ICT; and Built Environment and Design.

Figure 4.3 shows the fastest growing sub-fields in Canada, together with world growth rates. Canadian research output grew fastest in Nanoscience and Nanotechnology, Music, and Bioinformatics. Artificial Intelligence and Image Processing grew quickly in Canada, but more slowly than in the rest of the world, so that Canada's relative advantage in this field decreased, even with rapid growth. Apparent growth in sub-fields in the Social Sciences, and Visual and Performing Arts, may be mainly related to growth in journals in the Scopus database over this period.



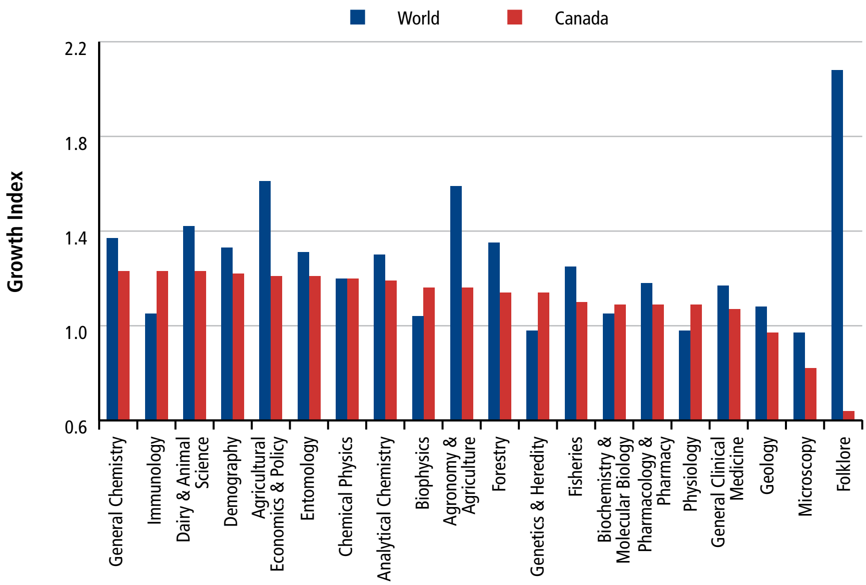
Data source: Calculated using bibliometric data from Science-Metrix derived from the Scopus database (Elsevier)

Figure 4.3

Top 20 Sub-Fields in Canada by Growth Index (GI)

In this figure sub-fields are shown ranked by Canada's Growth Index scores for 1999–2010, from highest to lowest.

Canada's absolute publication output declined in only 3 of 176 sub-fields between the periods 1999–2004 and 2005–2010: Geology, Microscopy, and Folklore (see Figure 4.4). The lowest rate of publication growth in Canada was seen particularly in several sub-fields in Agriculture, Fisheries, and Forestry (Agronomy and Agriculture, Dairy and Animal Science, Forestry, and Fisheries); and Biomedical Research (Biophysics, Genetics and Heredity, Physiology, and Microscopy) (see Figure 4.4). Many of these sub-fields, however, still had growth at or near the world average, and many of the sub-fields of slowest growth or decline, such as Geology, Physiology, Forestry, and Fisheries, are also among the largest sub-fields in Canada (see Table 4.3), and likely have less room for growth than smaller sub-fields.



Data source: Calculated using bibliometric data from Science-Metrix derived from the Scopus database (Elsevier)

Figure 4.4

Twenty Sub-Fields in Canada with the Lowest Growth Index (GI) Scores

In this figure sub-fields are shown by declining Growth Index scores for Canada. GI scores below 1.0 indicate an absolute decline in publication output between the periods 1999–2004 and 2005–2010.

4.2 CANADA'S RESEARCH IMPACT

Publication counts and their growth provide an indication of research output, but do not reflect the quality or impact of that research. In contrast, citations capture information about the degree to which published articles in a particular region or field have influenced the development of later research, in that field or any other field. Most bibliometric experts agree that such indicators provide useful insights on research impact, especially when used at higher levels of aggregation (i.e., fields rather than individual researchers). (Reviews of the issues associated with these types of indicators can be found in Chapter 2 and in Moed, 2005; REPP, 2005.)

Two different citation-based indicators were used for this report to gauge Canada's research impact. The first, Average Relative Citations (ARC), is a direct measure of how often research papers in a particular field or sub-field in Canada are cited compared to all papers published in that field or sub-field. ARC scores are expressed as an index in comparison to the world average. An ARC score of 1.0 indicates that a research paper is cited at the same level as the world average in that same field or sub-field. A score higher than 1.0 implies that the research is cited more frequently than the world average and a score below 1.0 implies the opposite. The second indicator is the share of the top-cited one per cent of scientific publications. Drawing from data compiled by Science-Metrix, the Panel calculated Canada's share of these highly cited publications — both in total and by field — for the period 2000–2008. The next sections present the results of these citation-based indicators regarding Canada's overall research impact, and its impact by field and sub-field.

4.2.1 Overall Research Impact

Based on ARC scores, Canada's research has a high level of overall impact, ranking sixth in the world in 2005–2010 among the top-producing scientific countries[12] (see Table 4.4). Canada's rank has held steady over the past decade. As seen in Table 4.4, ARC is not related to the size of the research enterprise and some small countries perform very well by this measure. For example, Switzerland is ranked first in the world, likely due in part to world-leading research being performed at the European Organization for Nuclear Research (CERN) by researchers from all over the world, which also contributes to its high collaboration rate (see Chapter 6).

Canada also performs well in terms of its share of the top-cited one per cent of scientific publications, accounting for 4.7 per cent of the world's most highly cited papers between 2000 and 2008 (see Table 4.4), compared to 4.1 per cent of total world publications (see Table 4.1).

12 All bibliometric rankings presented in the report are out of the top 20 countries (including "world") by output of scientific papers in that field or sub-field.

Table 4.4

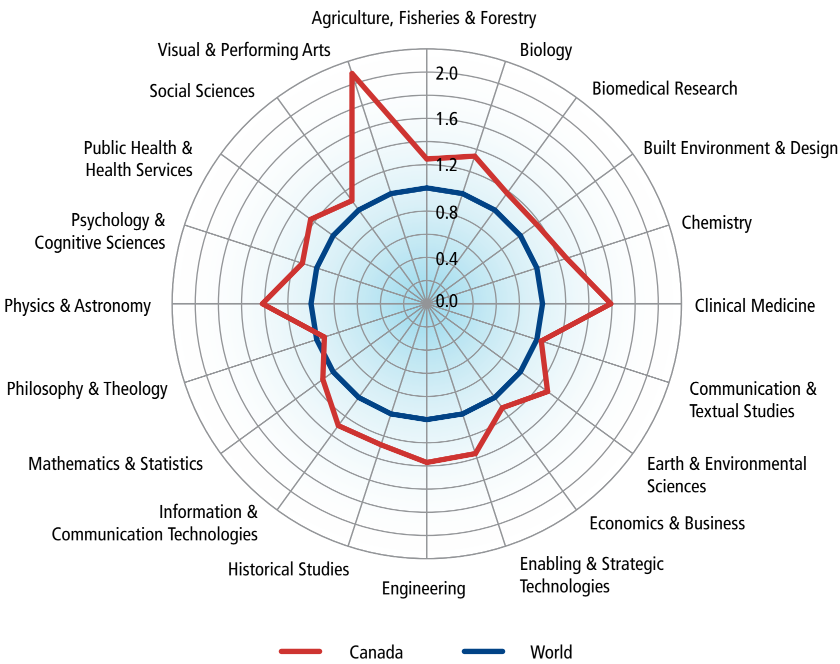
Key Bibliometric Indicators of Impact for Top-Producing Scientific Countries

Rank by ARC 2005–2010	Country	ARC 2005–2010	ARC 1999–2004	Percentage Share of Top-Cited 1% of Papers 2000–2008	Share of Top-Cited 1% of Papers/Share of Total Papers 2000–2008
1	Switzerland	1.62	1.46	2.20	1.38
2	Netherlands	1.50	1.37	2.72	1.22
3	Sweden	1.40	1.31	1.36	0.87
4	United States	1.40	1.38	40.05	1.38
5	United Kingdom	1.37	1.27	9.02	1.18
6	Canada	1.36	1.27	4.71	1.15
7	Australia	1.32	1.20	2.16	0.81
8	Germany	1.26	1.11	5.83	0.81
9	France	1.19	1.06	5.44	1.03
10	Italy	1.18	1.03	2.81	0.36
11	Spain	1.14	0.98	1.81	0.6
12	Rep. of Korea	0.93	0.91	1.04	0.43
13	Japan	0.88	0.84	2.81	0.71
14	Brazil	0.80	0.77	0.31	0.18
15	Turkey	0.80	0.69	0.45	0.36
16	India	0.77	0.64	0.70	0.26
17	China	0.74	0.70	5.45	0.46
18	Poland	0.72	0.63	0.27	0.18
19	Russia	0.53	0.47	0.16	0.07
	World	**1.00**	**1.00**	**100.00**	**1.00**

Notes: ARC=Average Relative Citations. Rankings are based on ARC scores for 2005–2010 and are out of the top 19 countries by total number of papers produced.
Data source: Calculated by Science-Metrix using Scopus database (Elsevier)

4.2.2 Research Impact by Field

The same citation-based indicators (used in Section 4.2.1) have also been used to identify the fields of research in which Canada has a high impact in comparison to other countries. In this case, high impact means that Canadian S&T is being cited by other researchers more frequently than the average research in the world. Evidence that this is happening is that researchers are citing (i.e., referencing) peer-reviewed articles by Canadians in their own peer-reviewed articles. For example, if Canadian astrophysicists capture an image of a newly discovered planetary system (see Spotlight on Astronomy and Astrophysics later in this chapter), that research will be published in a peer-reviewed journal. Because it is a ground-breaking discovery, other researchers around the world would cite that journal article when discussing this planetary system and the original article would become highly cited. Along with all other articles in Physics and Astronomy, this contributes to the field's Average (of all papers) Relative (to the rest of the world) Citation score. The findings are presented in Table 4.5 and Figure 4.5.



Data source: Calculated by Science-Metrix using Scopus database (Elsevier)

Figure 4.5

Average Relative Citations (ARC) Scores by Field of Research, 2005–2010

This figure shows the level of citation of research published by Canadians compared to world average levels of citation in that field of research.

Table 4.5

Key Bibliometric Indicators of Research Impact for Canada by Field of Research

	Rank by ARC 2005–2010	ARC 2005–2010	ARC 1999–2004	Percentage Share of Top-Cited 1% of Papers 2000–2008	Share of Top-Cited 1% of Papers/Share of Total Papers 2000–2008
Visual & Performing Arts	2	2.09	1.43	4.55	1.62
Clinical Medicine	3	1.59	1.49	6.15	1.60
Physics & Astronomy	3	1.42	1.26	2.57	0.89
General Science & Technology	4	2.51	1.36	3.27	0.95
Historical Studies	5	1.28	1.41	3.74	0.80
Psychology & Cognitive Sciences	5	1.13	1.09	5.39	0.73
General Arts, Humanities & Social Sciences	5	1.12	1.00	5.13	1.73
Engineering	6	1.37	1.21	4.44	1.05
Information & Communication Technologies	6	1.30	1.17	4.27	0.88
Biology	7	1.34	1.18	5.45	1.02
Chemistry	7	1.27	1.23	2.62	1.02
Public Health & Health Services	7	1.24	1.17	8.00	1.25
Economics & Business	7	1.11	1.06	3.96	0.79
Enabling & Strategic Technologies	8	1.36	1.41	3.77	1.30
Agriculture, Fisheries & Forestry	8	1.25	1.25	7.90	1.33
Social Sciences	8	1.10	1.15	4.05	0.88
Philosophy & Theology	8	0.93	0.88	3.31	0.60
Earth & Environmental Sciences	9	1.29	1.31	4.53	0.79
Biomedical Research	9	1.18	1.11	4.22	0.89
Mathematics & Statistics	9	1.11	1.09	3.29	0.79
Communication & Textual Studies	9	1.04	0.91	1.87	0.36
Built Environment & Design	14	1.17	1.08	4.81	0.89

Note: ARC=Average Relative Citations; Rankings are based on ARC scores for 2005–2010 and are out of the top 19 countries by total number of papers produced in that field of research.
Data source: Calculated by Science-Metrix using Scopus database (Elsevier)

As demonstrated, Canadian research in every field but one (Philosophy and Theology) was cited more frequently than the world average in 2005–2010, and was particularly highly cited in Visual and Performing Arts, Clinical Medicine, and Physics and Astronomy. In these three fields, Canada is ranked among the top three countries and has ARC scores significantly above the world average. Canada is also ranked among the top five countries in the fields of Historical Studies (for more depth on this field see Spotlight on History Research in Canada), and Psychology and Cognitive Sciences.

Spotlight on History Research in Canada

Historical Studies is a multifaceted field (including Anthropology, Archaeology, Classics, History, and Paleontology) that provides a unique account and perspective on the evolution of human society. Canadian history, in particular, was among the first disciplines in the humanities and social sciences to develop significant graduate studies in Canada, but the majority of Canadian-trained academic historians have been produced only since the 1960s. In the late 1960s and 1970s a number of specialized historical journals emerged to emphasize the new interests in various aspects of regional and social history — examples include *Acadiensis*, *BC Studies*, *Urban History Review*, *Histoire Sociale/Social History*, and *Labour/Le Travail*. Many of these journals were relatively late to digitize and hence are only now making their presence felt in the various databases that drive bibliometrics. Projects of national importance from earlier periods such as the ongoing *Dictionary of Canadian Biography*, *Historical Atlas of Canada*, *The Canadian Encyclopedia*, and the *Canadian Institute for Historical Microreproductions* are also now available in digital formats.

The history of science and technology has benefitted from the existence of the Canada Science and Technology Museum in Ottawa, which opened in 1967. The Canadian Science and Technology Historical Association and the Canadian Society for the History and Philosophy of Science provide a Canadian institutional framework for this sub-field as does *Scientia Canadensis*.

The history of medicine in Canada enjoyed considerable growth and maturation from the 1970s forward. Significant investments from Associated Medical Services in medical history chairs (at five Ontario universities in the 1970s and at McGill and Calgary later), reinvigoration of the Canadian Society for the History of Medicine, and the transformation of its journal the *Canadian Bulletin of Medical History* into an academic journal have also strengthened this field.

Considering all research fields (see Table 4.5), Canada's ARC scores place it among the top 10 countries in the world in every field, with the exception of Built Environment and Design. In most fields, Canada's research impact improved or held steady over the past decade, with significant increases in the fields of Visual and Performing Arts, Physics and Astronomy, Biology, Information and Communication Technologies, Engineering, and Communication and Textual Studies.

The final data column in Table 4.5 shows Canada's share of the top-cited one per cent of papers in each field between 2000 and 2008 as a proportion of the number of papers in the field. This measure provides a complementary, though slightly different, perspective on Canada's research impact across the various fields of research. A proportion greater than 1.0 means that more research than expected is among the top one per cent most highly cited, and a proportion below 1.0 means the opposite.

4.2.3 Research Impact by Sub-Fields

The same citation-based indicators used at the field level were also used to identify Canada's strengths at the sub-field level.[13] Table 4.6 shows the research sub-fields in which Canada ranks among the top three countries internationally, based on ARC scores for the 2005–2010 period. Of note is that Canada ranks first in the world in nine sub-fields, including:

- Dermatology and Venereal Diseases, and General and Internal Medicine (in the field of Clinical Medicine);
- Astronomy and Astrophysics, and Nuclear and Particle Physics (in the field of Physics and Astronomy);
- Business and Management (in the field of Economics and Business);
- Classics (in the field of Historical Studies);
- Criminology (in the field of Social Sciences);
- Anatomy and Morphology (in the field of Biomedical Research); and
- Zoology (in the field of Biology).

In some sub-fields where the distribution of publication output is particularly skewed around the world, it is possible to have an ARC score below 1.0 (indicating a level of citation below the world average) and yet place high in the country rankings. For example, Canada ranks second in the world in General Psychology and Cognitive Sciences (see Table 4.6), despite an ARC score of 0.9. When country ARC scores are compared for this sub-field, the United States is the only country with an ARC score above 1.0, and accounted for over half of all papers published in this sub-field during the period.

13 See Chapter 2 for a full listing of sub-fields.

Table 4.6

Sub-Fields where Canada is Ranked among the Top Three Countries in the World in terms of Average Relative Citations (ARC)

Sub-Field	Field	ARC 2005–2010	Rank by ARC
General & Internal Medicine	Clinical Medicine	3.93	1
Anatomy & Morphology	Biomedical Research	2.38	1
Dermatology & Venereal Diseases	Clinical Medicine	2.24	1
Astronomy & Astrophysics	Physics & Astronomy	1.86	1
Nuclear & Particles Physics	Physics & Astronomy	1.76	1
Classics	Historical Studies	1.74	1
Zoology	Biology	1.48	1
Business & Management	Economics & Business	1.38	1
Criminology	Social Sciences	1.37	1
Gastroenterology & Hepatology	Clinical Medicine	2.09	2
Anesthesiology	Clinical Medicine	1.87	2
Orthopedics	Clinical Medicine	1.49	2
Evolutionary Biology	Biology	1.42	2
History of Social Sciences	Historical Studies	1.37	2
Medical Informatics	Information & Communication Technologies	1.33	2
General Psychology & Cognitive Sciences	Psychology & Cognitive Sciences	0.90	2
General Physics	Physics & Astronomy	1.89	3
Industrial Engineering & Automation	Engineering	1.68	3
Urology & Nephrology	Clinical Medicine	1.67	3
Dairy & Animal Science	Agriculture, Fisheries & Forestry	1.64	3
Logistics & Transportation	Economics & Business	1.55	3
Mycology & Parasitology	Biology	1.55	3
Automobile Design & Engineering	Engineering	1.49	3
Surgery	Clinical Medicine	1.49	3
Design Practice & Management	Built Environment & Design	1.41	3
Speech-Language Pathology & Audiology	Public Health & Health Services	1.39	3
Information Systems	Information & Communication Technologies	1.38	3

Data source: Calculated by Science-Metrix using Scopus database (Elsevier)

Rankings are based on ARC scores for 2005–2010 and are out of the top 19 countries by total number of papers produced in that sub-field of research. Sub-fields are shown in order of ARC rank, and then by decreasing ARC score.

Spotlight on Astronomy and Astrophysics

Astronomy and astrophysics remains as inspiring and wondrous as it did hundreds of years ago. Yet today's astrophysicists make use of — and contribute to — cutting-edge technological developments, ranging from high-performance computing to artificial intelligence.

Broadly speaking, astronomy and astrophysics can be seen as addressing four fundamental questions: (1) *Where did it all come from?* This question addresses cosmology topics such as the origin of the universe, the Big Bang, and the nature of dark matter and dark energy; (2) *How did it all form?* This question considers the grand architecture of the universe and the formation of structure, from galaxies to stars to planets; (3) *How does it all work?* This question addresses the laws of physics as deduced from cosmic sources, which can act as laboratories of physics in extreme environments that are unattainable in terrestrial laboratories; and (4) *Are we alone?* This question considers the existence and origin of extra-solar planets as well as the possibility of extraterrestrial life.

Canada has world-leading researchers addressing practically all the above questions, often working in collaborations that span the country. This collaboration is facilitated by long-standing support from the Canadian Institute for Advanced Research, which brings together over two dozen researchers from eight Canadian institutions to study cosmology and other topical issues. Major astrophysics infrastructure with significant Canadian input includes the Gemini Observatory, James Clerk Maxwell Telescope and Canada-France-Hawaii Telescope, the Dominion Radio Astrophysical Observatory, the Atacama Large Millimeter/submillimeter Array and the Expanded Very Large Array. In space, Canada built the MOST (Microvariability and Oscillations of STars) satellite and made significant contributions to the Hubble Space Telescope, the Herschel satellite, and the upcoming James Webb Space Telescope.

Particularly noteworthy accomplishments of Canadian astronomy and astrophysics researchers in the past decade include the first direct image of a planetary system orbiting a nearby star; ground-breaking modelling and measurements of the cosmic microwave background, a remnant of the Big Bang; participation in the Millennium Run supercomputer simulation of galaxy evolution in the early universe; a unique confirmation of Einstein's Theory of General Relativity using a double pulsar system; and discovery of the most massive star known.

Table 4.7

Sub-Fields where Canada is not Ranked among the Top 10 Countries in the World in terms of Average Relative Citations (ARC)

Sub-Field	Field	ARC 2005–2010	Rank by ARC
Building & Construction	Built Environment & Design	1.24	11
Civil Engineering	Engineering	1.19	11
Environmental Engineering	Engineering	1.17	11
Dentistry	Clinical Medicine	1.07	11
Biophysics	Biomedical Research	0.99	11
Agricultural Economics & Policy	Economics & Business	0.97	11
Applied Mathematics	Mathematics & Statistics	0.96	11
Economics	Economics & Business	0.96	11
Geriatrics	Clinical Medicine	1.19	12
Forestry	Agriculture, Fisheries & Forestry	1.12	12
Behavioral Science & Comparative Psychology	Psychology & Cognitive Sciences	1.02	12
Ophthalmology & Optometry	Clinical Medicine	0.98	12
Microscopy	Biomedical Research	0.90	12
Mechanical Engineering & Transports	Engineering	1.29	13
Bioinformatics	Enabling & Strategic Technologies	0.94	13
Legal & Forensic Medicine	Clinical Medicine	0.94	13
Physiology	Biomedical Research	0.94	13
Science Studies	Social Sciences	0.89	13
Geology	Earth & Environmental Sciences	0.99	14
Political Science & Public Administration	Social Sciences	0.85	14
Development Studies	Economics & Business	0.67	14
Distributed Computing	Information & Communication Technologies	0.81	15
Strategic, Defence & Security Studies	Enabling & Strategic Technologies	0.86	16
Urban & Regional Planning	Built Environment & Design	0.86	17
Horticulture	Agriculture, Fisheries & Forestry	0.76	17
Gerontology	Public Health & Health Services	0.95	18

Data source: Calculated by Science-Metrix using Scopus database (Elsevier)

Rankings are based on ARC scores for 2005–2010 and are out of the top 19 countries by total number of papers produced in that sub-field of research. Sub-fields are shown in order of ARC rank, and then by decreasing ARC score.

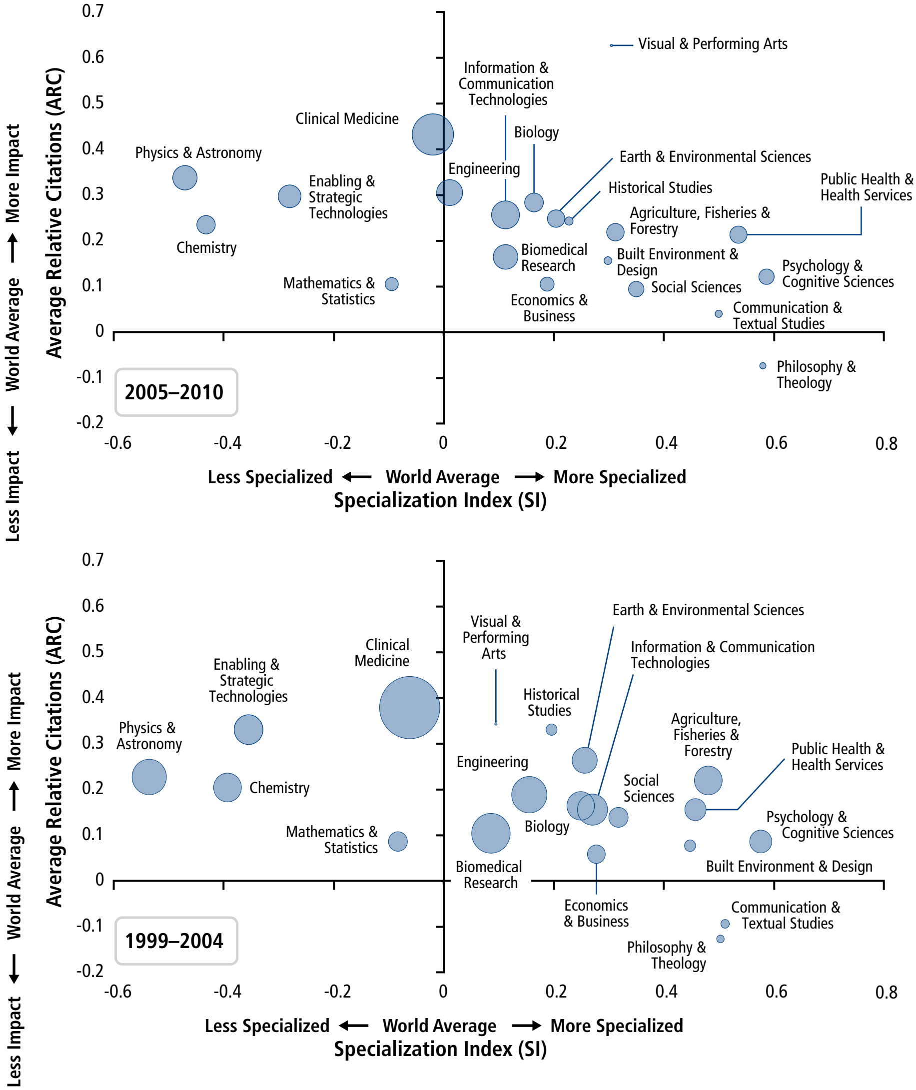
By ARC, Canada is ranked among the top 10 countries in the world in nearly all sub-fields. There are sub-fields, however, in which Canadian research has comparatively lower levels of citation, ranking below the top 10 countries in the world (see Table 4.7). Many of these sub-fields have ARC scores of less than 1.0 (i.e., below the world average).

4.3 SYNTHESIZING RESEARCH OUTPUT AND IMPACT

In identifying Canada's S&T strengths, it is important to take into account both research output and impact. Figure 4.6 combines output and impact-related bibliometric indicators for the 20 fields of research included in this study. The Specialization Index (SI), a measure of Canada's overall level of research activity in each field relative to the world average, is plotted on the horizontal axis. The ARC variable, a measure of the overall impact of Canadian research based on citations, is plotted on the vertical axis. The size of the bubble for each field corresponds to the total number of Canadian papers produced in that field. These diagrams are divided into four quadrants to show relative positioning of research fields:

- Fields in the top-right quadrant (the majority of Canadian fields) unequivocally represent areas of strength in Canada. Canadian research is both more highly cited than the world average for these fields, and these fields account for a higher proportion of Canadian publications than would be expected based on the world average.
- The top-left quadrant signifies potential areas of research opportunity for Canada. Fields positioned in this area have a high impact, but represent a lower proportion of Canadian publications than would be expected based on the world average.
- The bottom-left quadrant is associated with fields with low research impact and a low level of research output. Fields in this quadrant would be considered weak compared to other countries; however, none of the fields in Canada fall into this quadrant.
- In contrast, the bottom-right quadrant signifies areas where Canada has a relatively high level of research output, but a relatively low level of research impact.

As seen in these figures, Canadian research in most fields performs well when assessed by these benchmarks. Nearly all research fields in Canada were more highly cited than the world average in both periods, which suggests that Canadian research has a high level of impact across the board. As mentioned in Section 4.2.2, research in Visual and Performing Arts, Clinical Medicine, Physics and Astronomy, Engineering, and Enabling and Strategic Technologies stand out as being well above the world average based on citations. In the 2005–2010 period, all fields other than Philosophy and Theology were above the world average in terms of their ARC scores.



Data source: Calculated by Science-Metrix using Scopus database (Elsevier)

Figure 4.6

Positional Analysis of Canada in 20 Fields of Research in the Periods 2005–2010 and 1999–2004

Engineering is used as an example of how to read this figure. In the period 2005–2010 Engineering is higher on the y-axis (0.3) than in the period 1999–2004 (0.2), indicating that the bibliometric impact of research in Engineering in Canada has increased. Engineering is further to the left on the x-axis (0) than in the years 1999–2004 (0.17), indicating that the proportion of Canadian journal articles that are in Engineering has decreased compared with the world average proportion of journal articles that are in Engineering. Therefore, between the periods 1999–2004 and 2005–2010 this figure shows that Engineering increased in relative impact, but decreased in relative output. The size of the bubble is proportional to the number of publications in that field. ARC and SI scores are transformed in these figures to the hyperbolic tangent of the natural logarithm of the indicators in order to improve the readability of the figures and allow for a symmetrical representation of the data. Zero is equal to the world average for both axes.

The ARC scores increased in many fields between 1999–2004 and 2005–2010 (with these fields moving further up the vertical axis). This change is significant for several reasons. One potential driver of the increased level of impact is that an influx of new publications from emerging S&T countries such as China may have lower levels of citation and therefore serve to bring down world averages. A comparison between the two figures, however, reveals that SI scores in Canada are now more closely distributed around the world average than they were in the past. This suggests that Canadian research is now occurring in a more competitive landscape internationally — with less variation between Canada and other countries in terms of the overall concentration of research activity among different fields.

High ARC scores coupled with low SI scores, as is the case for Physics and Astronomy, and Chemistry, indicate areas of potential opportunity for Canada. This combination implies that although Canada does less research in these areas than would be expected relative to other countries, the research that is done is of high quality. Conversely, fields in the bottom right-hand quadrant have a relatively high level of output but a lower than average impact. Only one field, Philosophy and Theology, appears in this quadrant in the most recent time period.

4.4 COMPARISON WITH THE 2006 REPORT

In many respects, the core bibliometric results are directly comparable to those presented in the Council's 2006 S&T report. But there are two important differences in the current report:

- This report uses data from Elsevier's Scopus database. The Panel chose this data source for its greater coverage of research in the humanities, arts, and social sciences than the Thomson Reuters' Web of Science database, which was used for the 2006 report. Because of the different databases used, data have been recalculated for 1999–2004 using the Scopus database.
- This report uses ARC as the key indicator for research impact. ARC is a more direct measure of impact than the Average Relative Impact Factor (ARIF) used in the 2006 report. ARIF is based on the levels of citation of the journals in which research is published, rather than the levels of citation of the specific paper itself. The ARC variable was not available to the 2006 Panel on the State of Science and Technology in Canada. The two measures, however, are generally highly correlated.

Many of the findings reported in the 2006 report remain valid six years on. For example, Canada continues to have high-impact research in the areas (all named by their designations in the 2006 report) of Clinical Medicine and Physics; a high level of output in Psychology and Psychiatry, and Earth and Space Sciences; and a relatively low level of research output in Chemistry and Physics (CCA, 2006).[14]

However, differences also emerge in a comparison of the findings from the two reports. Although research output increased for most Canadian S&T over the past six years, output in some natural resource fields, such as Agriculture, Fisheries, and Forestry, declined. The strong performance of Physics and Astronomy is another key finding that differs from the 2006 report. While the Specialization Index remains low for this field, Canadian research in many areas of Physics and Astronomy is now highly cited. The improved analysis in the current report of the humanities, arts, and social sciences reveals that Canada produces high-impact research compared to its peers in Visual and Performing Arts, Historical Studies, Criminology, and Management and Business.

4.5 CONCLUSIONS

Bibliometric indicators are a valuable source of evidence in assessing Canada's research strengths relative to other countries. The production of peer-reviewed journal articles is a vital part of research activity in most fields of scientific work, and data drawn from patterns in the publications of these articles provide useful insights into many dimensions of research activity. In particular, these measures capture information about the overall output of research publications and the impact of those publications, as reflected by citations.

Building on the bibliometric analysis undertaken for the Council's 2006 State of S&T report, this chapter has surveyed a range of evidence based on these types of measures. The overall findings that emerge from this survey are both clear and encouraging. First, Canada remains one of the leading countries in terms of the overall output of scientific research. Canada's level of research output is particularly high in the fields of Psychology and Cognitive Sciences; Public Health and Health Services; Earth and Environmental Sciences; and Agriculture, Fisheries, and Forestry.

14 Field names discussed here are based on those used in the Council's 2006 S&T report.

Second, growth in Canada's research output over the last decade has been comparatively high. While most developed countries had rates of publication growth in the 30 to 40 per cent range, Canada's publication output grew by 59 per cent between the periods 1999–2004 and 2005–2010. In addition, Canada's share of world publications increased over this period. This increase is impressive given that growth in world output is heavily affected by rapidly growing research output in China, India, and Brazil. Fields of research activity in Canada that had the highest growth include Visual and Performing Arts, Philosophy and Theology, Physics and Astronomy, Enabling and Strategic Technologies, Clinical Medicine, and Public Health and Health Services. The level of growth in Public Health and Health Services, as well as Psychology and Cognitive Sciences, is impressive because these were among the largest fields by share of world papers in 1999–2004 (see Table 4.2). Other fields with a large share of world papers in 1999–2004 either declined (Agriculture, Fisheries, and Forestry; Built Environment and Design), or remained stable (Earth and Environmental Sciences), as might be expected when starting from a high baseline.

Third, Canada has a high level of research impact across all fields, with Canadian research more highly cited than the world average in all fields except Philosophy and Theology. In addition, Canada's level of research impact has increased over the past decade relative to the rest of the world — despite increasing international competition shown by the shrinking range of research specialization (SI scores) observed in many fields. Canada also accounts for 4.7 per cent of the world's top-cited one per cent of publications, higher than Canada's 4.1 per cent of all publications. Canada's research impact — as measured by ARC scores — is highest in the fields of Visual and Performing Arts, Clinical Medicine, and Physics and Astronomy, all of which rank among the top three countries in the world. Canadian research in nine sub-fields ranks first in the world by ARC: Anatomy and Morphology, Astronomy and Astrophysics, Business and Management, Classics, Criminology, Dermatology and Venereal Diseases, General and Internal Medicine, Nuclear and Particle Physics, and Zoology.

The evidence in this chapter clearly demonstrates that Canada remains one of the leading countries in the world both in terms of research productivity and research impact.

5

The Stature and Reputation of Canadian S&T

- Survey of Top-Cited International Researchers
- Survey of Canadian S&T Experts
- Comparison with the 2006 Report
- Conclusions

5 The Stature and Reputation of Canadian S&T

Key Findings

- Canadian S&T is highly regarded internationally. Among top-cited international researchers surveyed by the Panel, 37 per cent ranked Canada as one of the five leading countries in their field in terms of the originality, impact, and rigour of its S&T, placing Canada fourth highest in the world after the United States, United Kingdom, and Germany.
- The fields ranked highest by international researchers are Agriculture, Fisheries, and Forestry; Psychology and Cognitive Sciences; Public Health and Health Services; Social Sciences; Economics and Business; and Philosophy and Theology.
- For research fields in the natural and health sciences and engineering, Canada's international reputation in S&T is highly correlated with the field's share of the most cited papers in the world. This is not the case for fields in the humanities, arts, and social sciences, indicating that factors other than bibliometrics account for reputation in these fields.
- Although Canadian S&T experts surveyed by the Panel rated Canadian S&T as stronger than they did in 2006, they are also more likely to report that it is losing ground when compared to other countries.

The preceding chapter presented quantitative bibliometric evidence based on peer-reviewed literature. As described in Chapter 2, there is also considerable precedent for the use of qualitative opinion-based evidence in the assessment of S&T. For example, in many countries, including Canada, decisions regarding the funding of research projects by granting councils have long been made by grant selection committees — the expert opinion of peers (e.g., SSHRC, 2011). Opinion surveys have also been used to assess S&T performance and prospects at a national and international level (e.g., CCA, 2006; Battelle, 2010). This chapter explores Canada's reputation in S&T, both internationally and domestically, through two opinion surveys commissioned by the Panel: the survey of top-cited international researchers and the survey of Canadian S&T experts.

5.1 SURVEY OF TOP-CITED INTERNATIONAL RESEARCHERS

As described in Chapter 2, the Panel identified the authors of the top-cited journal articles in the world from 2000 to 2008 and asked them for their opinions on S&T in their sub-field.[15] The Panel received 5,154 responses out of the 44,868 emails successfully sent (excluding bounce backs) to researchers invited to participate in the survey.[16]

This chapter presents the results of questions 1 to 4 of the survey (see Box 5.1). Question 5 is discussed in Chapter 8.

> ***Box 5.1***
> **Summary of Questions Asked in the Survey of Top-Cited International Researchers**
>
> 1. Which of the following fields most closely matches your area of expertise? Which sub-field?
> 2. In your area of expertise, what are the five leading countries in terms of research originality, impact and rigour?
> 3. What is your opinion of Canada's research strength in your area of expertise, compared with other advanced countries?
> 4. In your research career have you visited, worked or studied at a Canadian research organization or collaborated with Canadian researchers?
> 5. Does Canada have particular infrastructure or research programs of worldwide importance?
>
> *The full list of survey questions is available in Appendix 5. This can be found at www.scienceadvice.ca.*

5.1.1 Breakdown of Survey Respondents

Survey respondents were from over 40 countries. Some countries (Canada, Italy, and Australia) had greater proportional representation in the survey respondents than the sample population (see Table 5.1). In contrast, the United States, China, and Japan were less represented among respondents than in the sample.

15 Methodological details can be found in Chapter 2. Additional data can be found in Appendix 5 at www.scienceadvice.ca.

16 The response rate was 11.5 per cent. The survey results are valid within a margin of error of +/-1.3 percentage points, 19 times out of 20. This margin of error increases for sub-group results (e.g., field level analysis).

Table 5.1
Sample and Respondent Breakdown by Country

	Number of authors in sample	Percentage of total sample	Number of survey responses received	Percentage of total survey responses received
United States	22,117	41.0	1,721	33.4
United Kingdom	4,737	8.8	489	9.5
Germany	3,350	6.2	281	5.5
China	2,966	5.5	144	2.8
Canada	2,360	4.4	360	7.0
France	2,210	4.1	238	4.6
Japan	1,616	3.0	97	1.9
Italy	1,551	2.9	223	4.3
Netherlands	1,511	2.8	148	2.9
Australia	1,239	2.3	156	3.0
Switzerland	1,226	2.3	118	2.3
Other	9,071	16.8	1,179	22.9
Total	**53,954**	**100.0**	**5,154**	**100.0**

Because the responding population was significantly different than the sample population ($p<0.01$) for some countries, the data were weighted to correct for over- or under-representation. For example, Canadians accounted for 4.4 per cent of top-cited researchers, but 7.0 per cent of those that responded. After weighting, Canadians account for 4.4 per cent in the analyses that follow. This weighting changed overall results of how many people ranked each country in the top five by less than one per cent.

Even with weighting to remove bias in choice to respond, there could be a perception that self-selection is responsible for some results. Top-cited Canadian researchers in the population sample were not excluded from the survey but the results for Canada cannot be explained by self-promotion since 37 per cent of all respondents identified Canada among the top five countries in their field, but only 7 per cent (4.4 per cent after weighting) of respondents were from Canada. Similarly, 94 per cent of respondents identified the United States as a top country in their field, yet only 33 per cent (41 per cent after weighting) were from the United States. Furthermore, only 9 per cent of respondents had either worked or studied in Canada, and 28 per cent had no personal experience of, or association with, Canada or Canadian researchers (see Table 5.2). It is reasonable to conclude that the vast majority of respondents based their evaluation of Canadian S&T on its scientific contributions and reputation alone.

Table 5.2

Respondents' Association with Canada

Response to question asking the extent of a survey respondent's previous association with Canada		
Response	**Frequency**	**Percentage**
No, never	1,446	28.0
Yes, I have worked as a researcher in a Canadian university	403	7.8
Yes, I have worked as a researcher in a Canadian business	5	0.1
Yes, I have studied in Canada	56	1.1
Yes, I have collaborated with Canadian researchers	994	19.3
Yes, I have visited	2,231	43.3
Don't know/No response	20	0.4
Total	**5,154**	**100.0**

5.1.2 Canada's Research Reputation

The survey results indicate that Canadian S&T is well regarded by the world's top-cited researchers. Overall, 37 per cent of respondents listed Canada as one of the top five countries worldwide in their research sub-field (see Figure 5.1). Canada was ranked as a top country fourth most often, behind the United States, the United Kingdom, and Germany.[17]

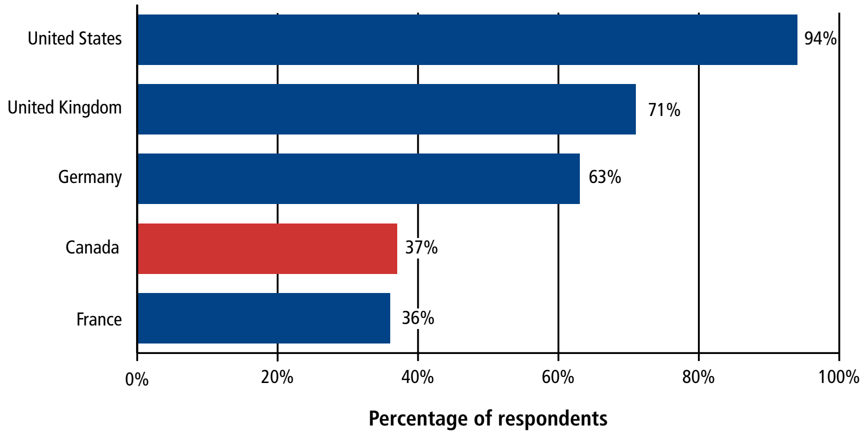


Figure 5.1

Top Five Countries by S&T Reputation Internationally

This figure shows the percentage of survey respondents that identified each country as one of the top five in the world in their area of research. Only the five most highly ranked countries are shown. Thirty-seven per cent of all survey respondents identified Canada as one of the leading countries in the world in their field.

17 There is potential for English-language bias in these results. English is used as the common language in most scientific publications, and countries where S&T is commonly carried out in a language other than English (such as Japan, Republic of Korea, and China) may be disadvantaged.

Furthermore, two-thirds of respondents stated that Canadian research was strong in their own research field as compared with other advanced countries (see Figure 5.2), and 42 per cent of respondents evaluated Canada as "very strong."

Canada's reputation for excellence extends across many research fields. Figure 5.3 shows the countries ranked highest in terms of the percentage of researchers ranking them among the top five countries in each field. The United States was ranked first in the world in all but one research field, meaning that more respondents listed the United States as one of the top five countries in the world in their field than any other country. Canada appears among the top five countries in three-quarters of the fields. It ranked second in the world in Agriculture, Fisheries, and Forestry. It ranked third in Economics and Business, Philosophy and Theology, Psychology and Cognitive Sciences, Public Health and Health Services, and Social Sciences. In 11 fields, 40 per cent or more of respondents ranked Canada among the top five countries worldwide.

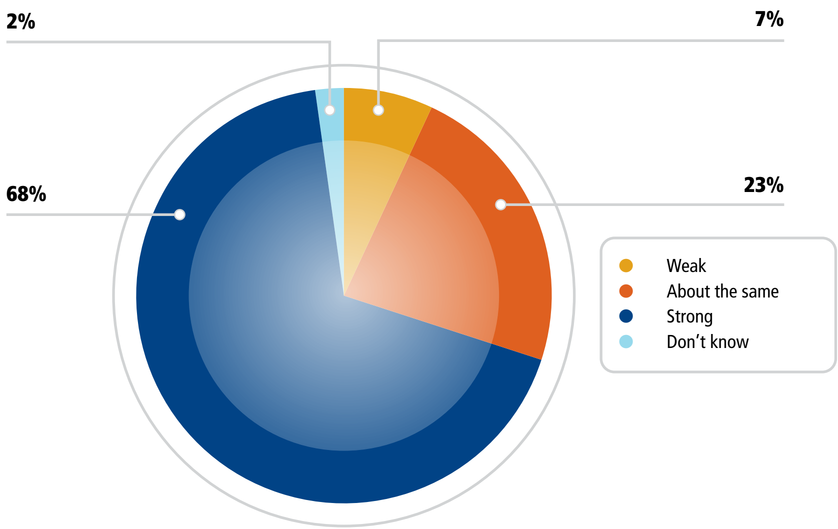
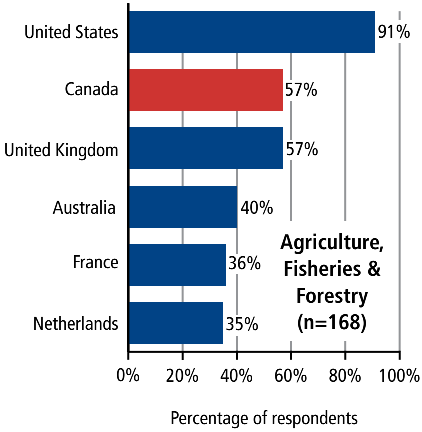
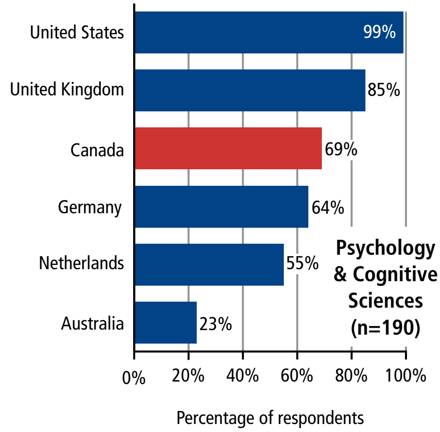


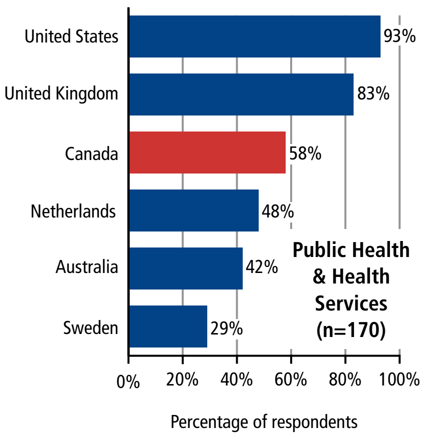
Figure 5.2

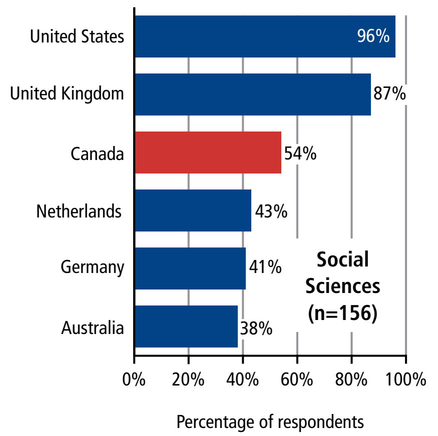
Canada's International Reputation in S&T

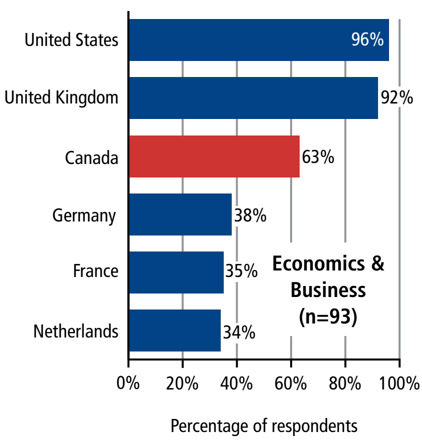
This figure shows the percentage of respondents identifying Canada as "strong" (5 to 7 on a 7-point scale), "about the same" (4 on a 7-point scale) or "weak" (1 to 3 on a 7-point scale) in their research field compared with other advanced countries.

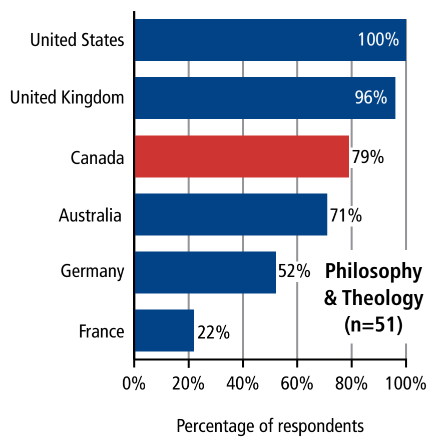

United States
Canada
United Kingdom
Australia
France
Netherlands
91%
57%
57%
40%
36%
35%
Agriculture, Fisheries & Forestry (n=168)
0% 20% 40% 60% 80% 100%
Percentage of respondents

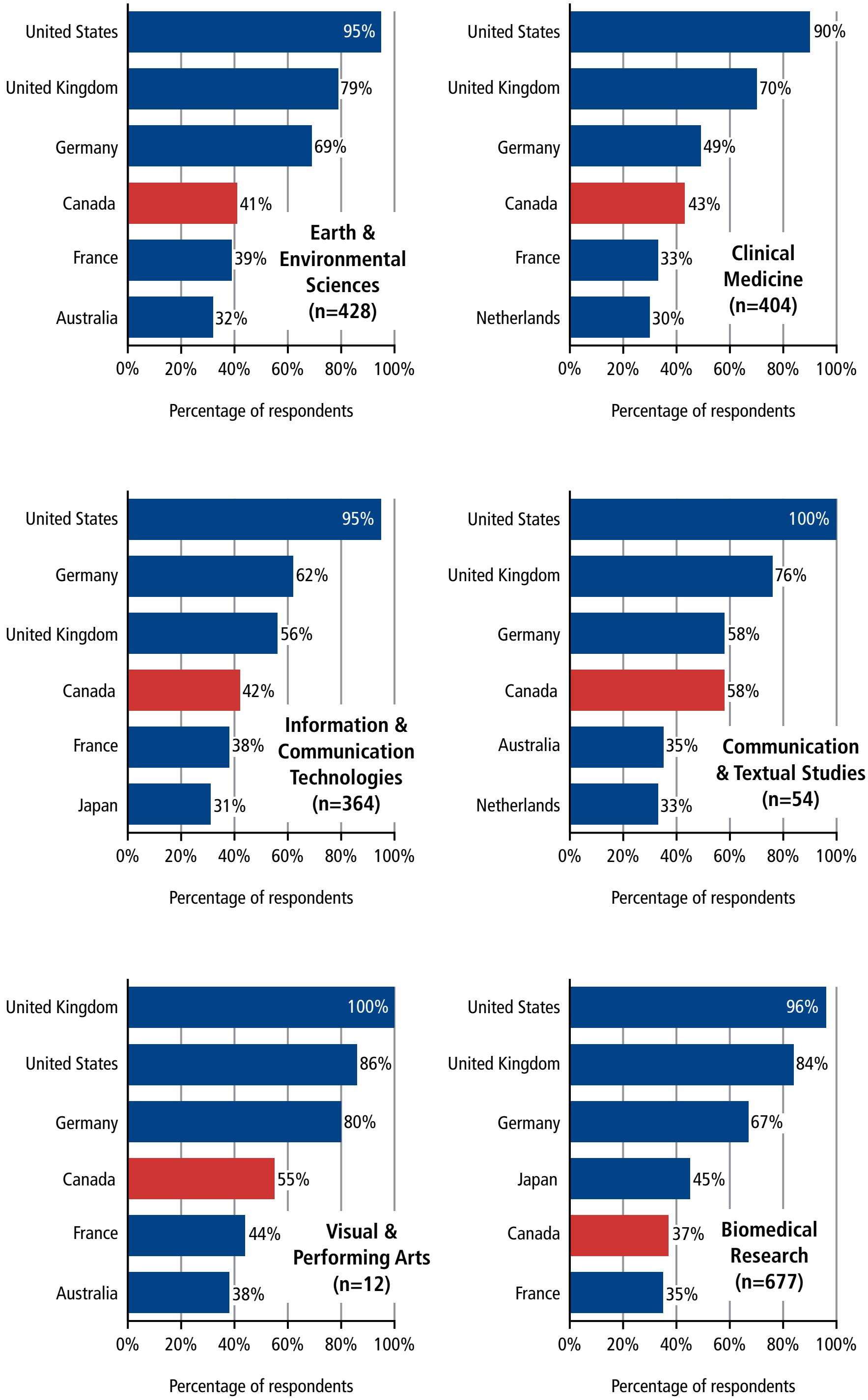

United States
United Kingdom
Canada
Germany
Netherlands
Australia
99%
85%
69%
64%
55%
23%
Psychology & Cognitive Sciences (n=190)
0% 20% 40% 60% 80% 100%
Percentage of respondents

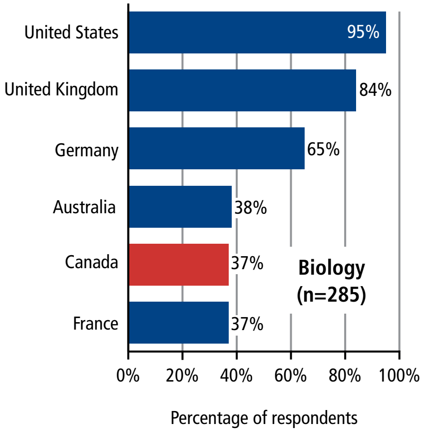

United States
United Kingdom
Canada
Netherlands
Australia
Sweden
93%
83%
58%
48%
42%
29%
Public Health & Health Services (n=170)
0% 20% 40% 60% 80% 100%
Percentage of respondents

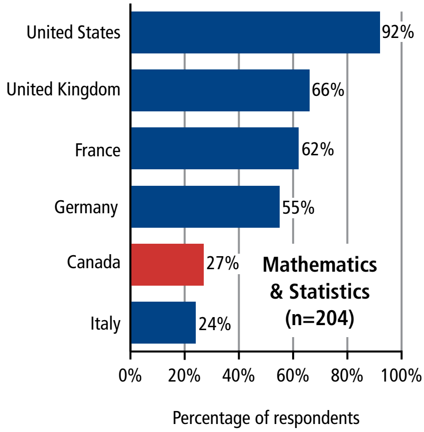

United States
United Kingdom
Canada
Netherlands
Germany
Australia
96%
87%
54%
43%
41%
38%
Social Sciences (n=156)
0% 20% 40% 60% 80% 100%
Percentage of respondents

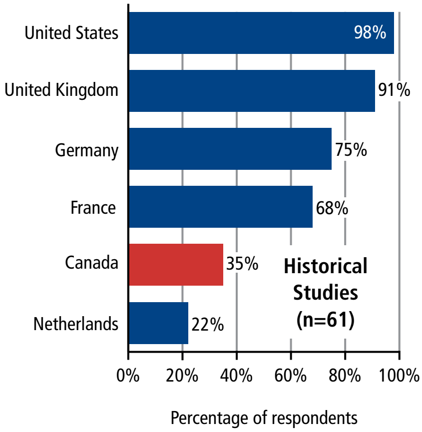

United States
United Kingdom
Canada
Germany
France
Netherlands
96%
92%
63%
38%
35%
34%
Economics & Business (n=93)
0% 20% 40% 60% 80% 100%
Percentage of respondents

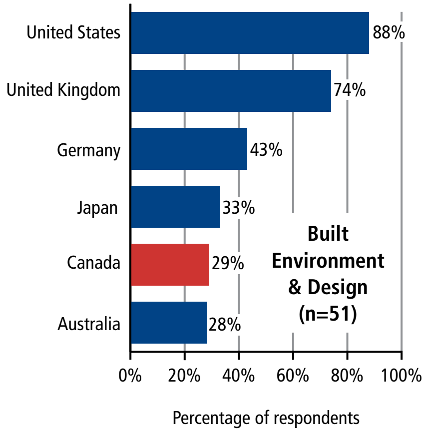

United States
United Kingdom
Canada
Australia
Germany
France
100%
96%
79%
71%
52%
22%
Philosophy & Theology (n=51)
0% 20% 40% 60% 80% 100%
Percentage of respondents

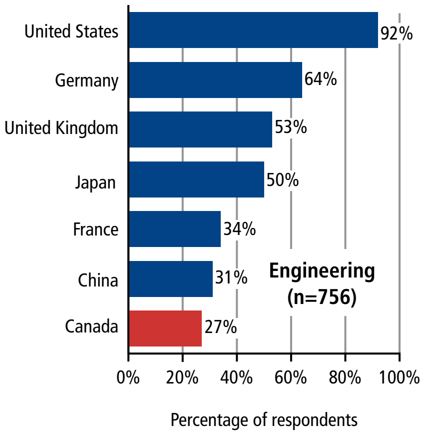

Earth & Environmental Sciences (n=428)
United States 95%
United Kingdom 79%
Germany 69%
Canada 41%
France 39%
Australia 32%
Clinical Medicine (n=404)
United States 90%
United Kingdom 70%
Germany 49%
Canada 43%
France 33%
Netherlands 30%
Information & Communication Technologies (n=364)
United States 95%
Germany 62%
United Kingdom 56%
Canada 42%
France 38%
Japan 31%
Communication & Textual Studies (n=54)
United States 100%
United Kingdom 76%
Germany 58%
Canada 58%
Australia 35%
Netherlands 33%
Visual & Performing Arts (n=12)
United Kingdom 100%
United States 86%
Germany 80%
Canada 55%
France 44%
Australia 38%
Biomedical Research (n=677)
United States 96%
United Kingdom 84%
Germany 67%
Japan 45%
Canada 37%
France 35%
0% 20% 40% 60% 80% 100%
Percentage of respondents

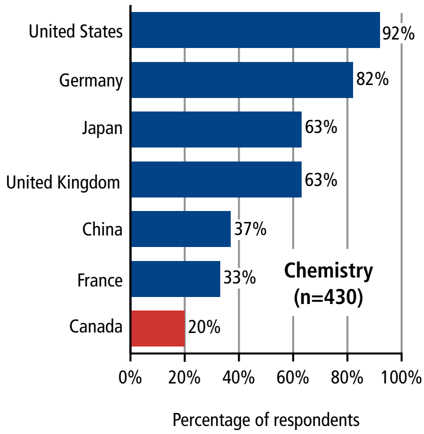

United States
United Kingdom
Germany
Australia
Canada
France
95%
84%
65%
38%
37%
37%
Biology
(n=285)
0%
20%
40%
60%
80%
100%
Percentage of respondents


United States
United Kingdom
France
Germany
Canada
Italy
92%
66%
62%
55%
27%
24%
Mathematics
& Statistics
(n=204)
0%
20%
40%
60%
80%
100%
Percentage of respondents


United States
United Kingdom
Germany
France
Canada
Netherlands
98%
91%
75%
68%
35%
22%
Historical
Studies
(n=61)
0%
20%
40%
60%
80%
100%
Percentage of respondents


United States
United Kingdom
Germany
Japan
Canada
Australia
88%
74%
43%
33%
29%
28%
Built
Environment
& Design
(n=51)
0%
20%
40%
60%
80%
100%
Percentage of respondents


United States
Germany
United Kingdom
Japan
France
China
Canada
92%
64%
53%
50%
34%
31%
27%
Engineering
(n=756)
0%
20%
40%
60%
80%
100%
Percentage of respondents


United States
Germany
Japan
United Kingdom
China
France
Canada
92%
82%
63%
63%
37%
33%
20%
Chemistry
(n=430)
0%
20%
40%
60%
80%
100%
Percentage of respondents

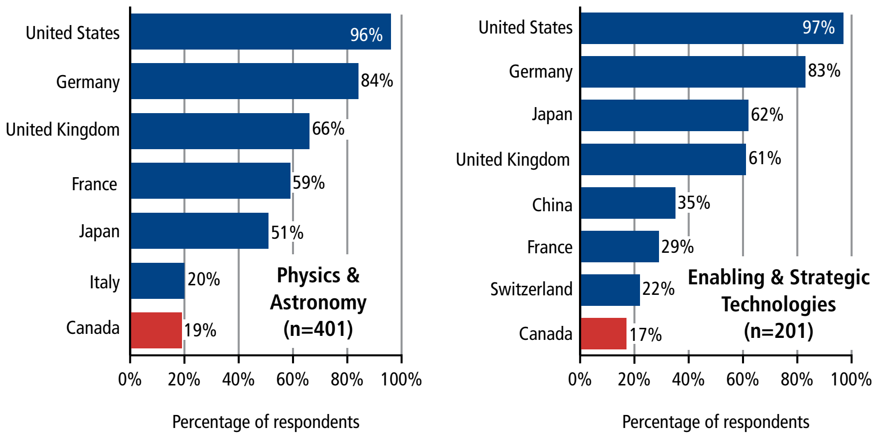


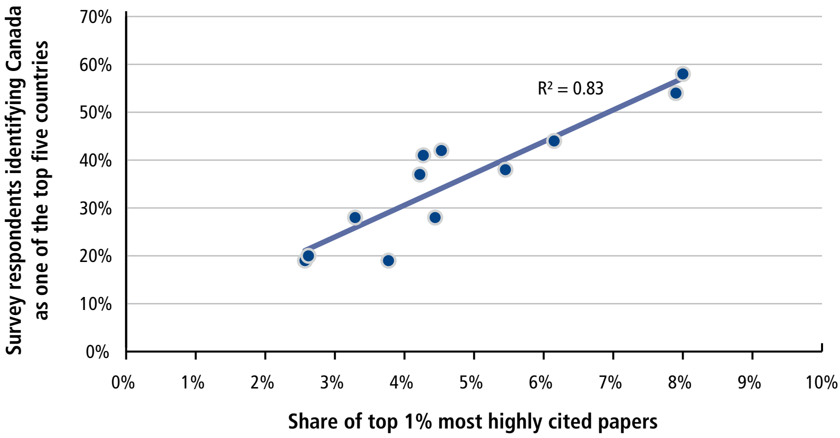
Figure 5.3

Results of Survey of Top-Cited International Researchers for each Field

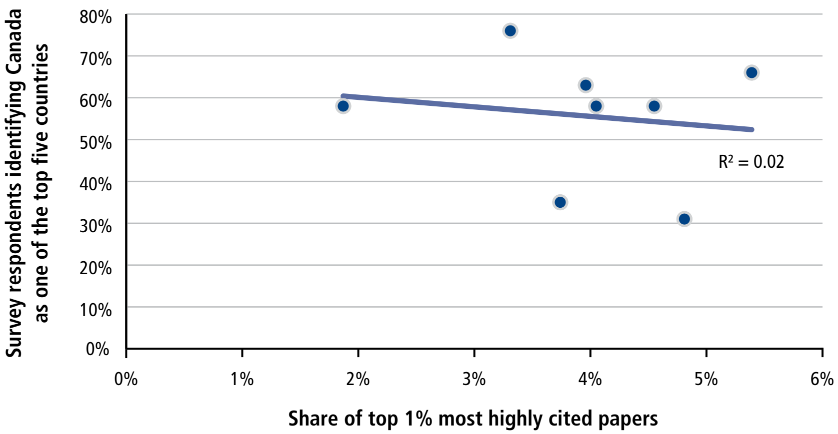
Each bar chart shows the weighted percentage of respondents that ranked each country among the top five in their field. "n" refers to the number of respondents identifying that field as their area of expertise. Fields are listed in the order of Canada's world ranking by top-cited researchers, then by the number of respondents.

In several fields there is considerable concordance between the survey results and bibliometric ARC rankings (see Chapter 4). For example, in Psychology and Cognitive Sciences, Visual and Performing Arts, Historical Studies, and Clinical Medicine, Canada is ranked among the top five in the world by both measures. There are, however, frequent discrepancies between the two sets of data. For example, Philosophy and Theology was ranked in the top five by 79 per cent of survey respondents — the highest of all fields — yet its ARC is below the world average. Figure 5.4 may help explain these observations, at least in part. The figure shows that for the natural sciences, engineering, and health sciences (5.4a), the percentage of survey respondents identifying Canada in the top five in the world is highly correlated with Canada's share of the world's top one per cent of papers in the field (as listed in Table 4.4). In contrast, for fields in the humanities, arts, and social sciences[18] (5.4b), the lack of correlation between the survey results and the field's share of top-cited papers suggests that international reputation in these fields is largely dependent on factors other than bibliometrics such as books and book chapters (see Section 2.4).

18 Fields in the humanities, arts, and social sciences had lower numbers of survey responses, in general, than fields in the natural and health sciences, and engineering, meaning the statistical level of confidence in the results is lower.



a) Natural and Health Sciences and Engineering



b) Humanities, Arts, and Social Sciences

Source: The share of world papers was calculated by Science-Metrix using the Scopus database (Elsevier)

Figure 5.4

The Relationship between Bibliometrics and Reputation

This figure shows the relationship between Canada's share of the top one per cent most highly cited papers and the percentage of top-cited researchers naming Canada in the top five in each field in a) the natural and health sciences and engineering, and b) the humanities, arts, and social sciences. Each data point represents a single field.

Regardless of the reasons behind international opinions of Canadian research, the overall message is clear: Canadian research is highly regarded internationally.

5.2 SURVEY OF CANADIAN S&T EXPERTS

The Panel's survey of Canadian S&T experts (see Box 5.2) complemented the international survey and provided a comparison with a similar survey performed for the Council's 2006 S&T report. Of the 8,513 Canadian S&T experts targeted for this survey, 679 responded.[19,20]

This chapter presents the results of questions 1 and 4. Question 2 is discussed in Chapter 8, and question 3 in Chapter 6.

Box 5.2
Summary of Questions Asked in the Survey of Canadian S&T Experts

1. For each sub-field you feel comfortable providing your opinion on please rate: Canada's research strength in terms of originality, impact, and rigour compared to other advanced countries; the trend in relative strength over the past five years; and which three provinces/ territories have the greatest strength in that sub-field?
2. Which elements of Canada's S&T infrastructure confer significant advantages relative to other advanced countries?
3. Among research areas of increasing significance, in which is Canada best placed to be among the global leaders? Choose up to five.
4. Taking into account all aspects of Canadian S&T, what is Canada's overall state compared with other advanced countries, and what is the trend over the past five years?

The full list of survey questions is available in Appendix 6. This can be found at www.scienceadvice.ca.

The survey results show that Canada is considered to be strong compared with other advanced countries across all fields, but particularly in Agriculture, Fisheries, and Forestry; Mathematics and Statistics; Earth and Environmental Sciences; and Engineering. Over 70 per cent of respondents identified each of these fields

19 The response rate was 8.0 per cent. The survey results are valid within a margin of error of +/- 3.6 percentage points, 19 times out of 20. This margin of error increases for sub-group results (e.g., field level analysis).

20 Methodological details can be found in Chapter 2. Additional data can be found in Appendix 6 at www.scienceadvice.ca.

as strong (see Table 5.3). This view of Canada's strength, as compared with other advanced countries, is consistent with the findings of the international survey.

When asked about trends, Canadian S&T experts reported most fields to be stable. For Public Health and Health Services, Mathematics and Statistics, Visual and Performing Arts, and Communication and Textual Studies, over 20 per cent of respondents felt the field was gaining ground. In contrast, over 20 per cent of respondents were concerned that Canada is falling behind in Chemistry, Earth and Environmental Sciences, and Enabling and Strategic Technologies — fields in which Canada also performs less well by bibliometric measures (see Chapter 4).

Table 5.3

Opinions of Canadian S&T Experts on the Strength and Trends of each Field Compared with Other Advanced Countries

Field	Percentage of respondents			Percentage of respondents		
	Strong	About the same	Weak	Gaining ground	Stable	Falling behind
Public Health & Health Services	65	31	5	26	64	10
Mathematics & Statistics	76	20	4	24	62	15
Visual & Performing Arts	68	18	14	22	72	6
Communication & Textual Studies	55	32	13	21	66	14
Psychology & Cognitive Sciences	67	27	6	15	81	4
Economics & Business	66	30	5	14	80	6
Enabling & Strategic Technologies	62	34	4	13	66	21
Philosophy & Theology	65	30	5	12	82	6
Social Sciences	60	34	6	12	77	11
Earth & Environmental Sciences	71	22	7	10	64	26
Built Environment & Design	50	36	14	10	83	7
Historical Studies	53	35	12	9	76	15
Engineering	70	27	3	8	74	17
Biomedical Research	62	35	3	8	74	18
Physics & Astronomy	56	40	4	8	83	10
Agriculture, Fisheries & Forestry	78	19	3	7	75	19
Clinical Medicine	55	39	6	7	78	16
Chemistry	53	45	2	6	66	29
Information & Communication Technologies	64	29	7	5	82	12
Biology	57	33	10	5	79	16

Notes: Table is sorted by "Gaining ground" (highest to lowest). Strength was ranked on a 7-point scale, ratings from 5 to 7 are reported as "Strong," a rating of 4 is reported as "About the same," and a rating of 1 to 3 is reported as "Weak." Respondents were asked for opinions at the sub-field level. These have been aggregated to produce the results in this table. Results for all sub-fields can be found in Appendix 6 at wwwscienceadvice.ca.

5.2.1 Comparison of International and Canadian Surveys

As described in this chapter, the Panel conducted two different surveys with different methods in order to gain opinions on the state of S&T in Canada. Although the sampling methodologies and the questions asked were different in each survey, there was one question common to both surveys, asking respondents to rank Canada's research against other advanced countries on a 7-point scale, where 5 or above is strong. Figure 5.5 shows that, in general, Canadians are less likely to rate a field as strong compared with top-cited researchers from around the world.

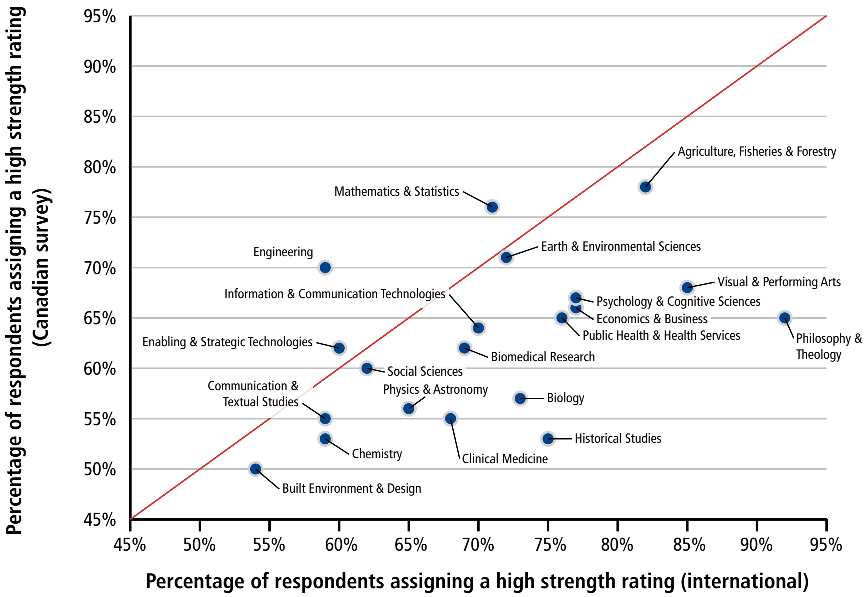


Figure 5.5

Comparison of Perceptions of Canadian Strength by Top-Cited International Researchers and Canadian S&T Experts

This figure shows percentages of survey respondents rating Canada as strong (5 to 7 on a 7-point scale). The line shows where both surveys have equal percentages. Fields above the line are rated more highly by Canadians, fields below the line are rated more highly by top-cited international researchers.

In the Panel's opinion, although both surveys are relevant, the international survey is more reliable because those surveyed were asked to respond only in their one sub-field of expertise, whereas Canadian S&T experts were invited to rate any sub-field for which they felt they had sufficient knowledge. The number of respondents was also much higher in the international survey.

5.3 COMPARISON WITH THE 2006 REPORT

A survey of the top-cited international researchers was not conducted in 2006, and is an important new addition, bringing an outside perspective on Canadian S&T.

The opinion survey of Canadian S&T experts undertaken for this report was similar to that conducted for the 2006 study. The key differences were this survey's use of the new classification of research fields and sub-fields from Science-Metrix to ensure compatibility of its findings with other elements of this assessment, and the different sampling methodology (see Chapter 2). As a result, findings from the 2006 and 2011 surveys cannot be compared accurately at the level of sub-fields, and even field-level identifications may differ. In general, however, average strength ratings were higher in the 2011 survey. In 2006, only three broad areas were identified as strong by more than 60 per cent of respondents; in 2011, 13 of the 22 research fields were so rated.

Neither the humanities and arts, nor the social sciences received particularly strong ratings in the 2006 survey. When these broad areas were assessed at the field level in 2011, however, several fields received relatively high rankings. Most notably these fields were Visual and Performing Arts, Psychology and Cognitive Sciences,[21] Economics and Business, and Philosophy and Theology.

The most comparable aspect of the two surveys is the evaluation of Canada's overall S&T strength and trends. When compared with answers to exactly the same questions in 2006, Canadian S&T experts in 2011 stated that Canada has become stronger in terms of S&T since 2006. They were more likely to say, however, that in terms of trends, Canada was losing ground compared to other countries (see Table 5.4). This latter perception may be related to a generic concern about levels of investment in research relative to Canada's main S&T competitors, and emerging S&T nations such as China and India, as opposed to a specific concern that their own field of research is losing ground (see Table 5.3).

Table 5.4

Opinions on the Overall State of Canadian S&T from the 2011 Survey Compared with Opinions from the 2006 Survey

	Strong (%)	Average (%)	Weak (%)	Gaining ground (%)	Stable (%)	Losing ground (%)
2006	46	28	26	28	33	39
2011	57	29	14	15	35	50

21 Psychology and Cognitive Sciences contains sub-fields which would normally be considered in the health sciences, natural sciences, and the social sciences.

5.4 CONCLUSIONS

Both the international and the Canadian surveys provide strong evidence that Canadian S&T is highly regarded. In the survey of the top-cited international researchers, Canada ranked fourth out of all countries in terms of how often it was identified as a world leader; and two-thirds of all respondents indicated that Canada had significant strength in their field of research compared with other countries. Canadian S&T experts appeared to concur, with 57 per cent of respondents indicating that Canada's overall S&T system is strong in comparison to other countries, although in general Canadians tend to underrate Canadian science when compared with top-cited international researchers. Taken together, results of the two surveys provide a strong endorsement of Canada's research enterprise, particularly when combined with other lenses used in this assessment, such as bibliometrics. This synthesis is performed in Chapters 10 and 11.

6

Collaboration, Clusters, and Emerging Technologies

6 Collaboration, Clusters, and Emerging Technologies

Key Findings

- Canadian researchers collaborate extensively with researchers in other leading countries, including the United States, the United Kingdom, France, Germany, China, and Japan.
- Canada's level of collaboration is particularly high in Visual and Performing Arts and Clinical Medicine.
- Based on a bibliometric analysis of research clusters, Canada is producing high-impact research related to several clusters in medicine and physics, and is highly active in clusters related to geology and mineral extraction.
- 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.
- According to Canadian S&T experts, Canada is well positioned to become a global leader in technologies related to personalized medicine and health care, and energy.

The evidence on Canada's S&T strengths presented in Chapter 4 relied primarily on standard bibliometric techniques related to publication and citation counts. Those indicators, however, do not encompass all the dimensions of S&T activity. In particular, standard bibliometrics does not identify patterns of collaboration among researchers, and may not adequately capture research activity with an interdisciplinary character.

This chapter provides a selection of evidence that is drawn from more advanced bibliometric techniques (see Box 6.1) designed to analyze these additional aspects of the scientific landscape. In particular, it identifies patterns of collaboration between Canadian researchers and those in other countries (based on the co-authorship of research papers); and clusters of related research papers, an alternative approach to assessing Canada's research strengths. These techniques are at the leading edge of bibliometric research and therefore not as well tested or accepted as traditional bibliometrics, but their potential to transcend disciplinary boundaries imposed from the top-down makes them important. The chapter's final section provides evidence from the survey of Canadian S&T experts on the areas of emerging technologies in which Canada is well positioned to become a global leader.

Box 6.1
Bibliometric Indicators Used in this Chapter

Number of International Collaborations: The number of publications by country and/or field in which there is at least one co-author affiliated with an institution in another country.

Collaboration Index (CI): An index that measures the extent of research collaboration in a country and/or field in proportion to the overall volume of publication output in that country. An index value greater than 1.0 indicates a higher level of collaboration than expected based on the number of papers produced, and an index value less than 1.0 indicates a lower level of collaboration than expected.

Collaboration Affinity (CA): A measure of the degree to which one country collaborates with another country based on co-authored publications. CA is based on an asymmetric computation of the Collaboration Index (the fact that Canada has a strong collaboration affinity with a country does not necessarily imply that that country will have a strong collaboration affinity with Canada). An index value greater than 1.0 indicates a higher level of collaboration than expected, and an index value less than 1.0 indicates a lower level of collaboration than expected.

For a more detailed explanation of methods used in calculating each of these indicators, see Appendix 1.

6.1 INTERNATIONAL RESEARCH COLLABORATION IN CONTEXT

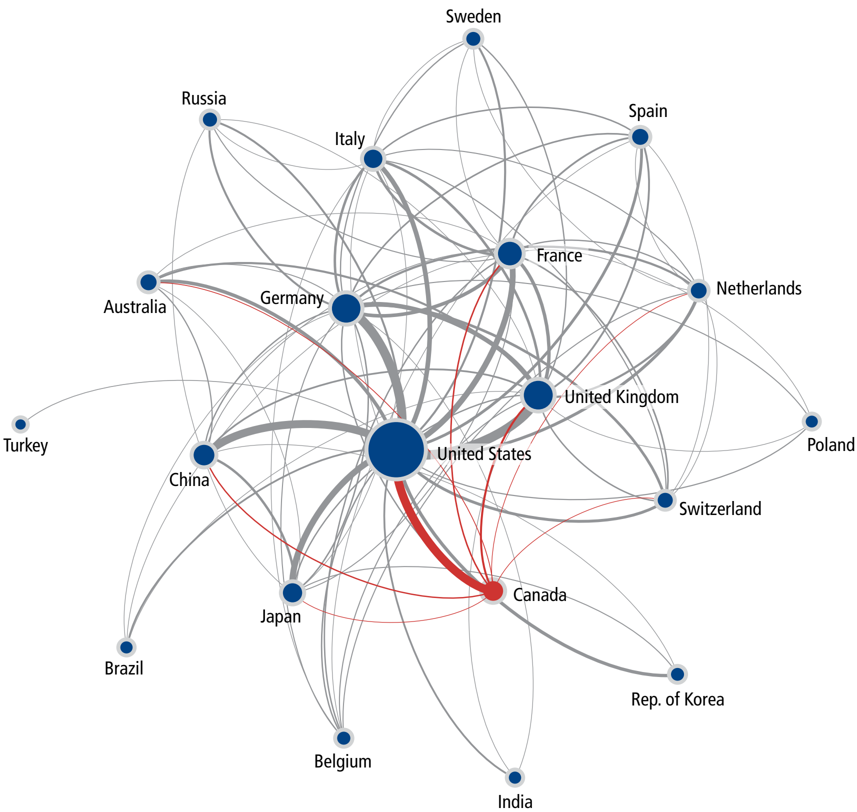
Scientific research is an increasingly collaborative endeavour. Currently over 35 per cent of articles published in international scientific journals have authors from more than one country — up from 25 per cent 15 years ago (Royal Society, 2011). This increase is being driven by many factors. New developments in telecommunication technology have made collaboration among countries faster, easier, and cheaper. In addition, scientific research itself is increasingly globalized. Countries such as China, India, and Brazil have rapidly growing scientific establishments that provide new opportunities for collaboration. Finally, new networks and communities are forming (both virtual and physical) that connect researchers to their counterparts around the world, thus facilitating collaboration (see Royal Society (2011) for a recent review of trends in global scientific collaboration).

Collaboration, however, should not necessarily be interpreted as a mark of quality. In some cases, a high level of international collaboration may be seen as an indication that Canadian research activity in a particular area commands worldwide interest. In other cases, a comparatively low level of international collaboration may simply denote an area of research of uniquely Canadian importance. Research collaborations can also be initiated in response to public policy signals. Many research funding programs now specifically aim to catalyze research collaboration. For example, the European Union's Framework Programme, which will finance €10 billion of research in 2012 (European Commission, 2011), requires that applications include researchers from more than one country, and has encouraged considerable intra-European collaboration (European Commission, 2012).

6.2 GLOBAL RESEARCH COLLABORATION

S&T is a global endeavour, with researchers seeking out the best facilities and partners worldwide. Figure 6.1 illustrates the global research collaboration network based on patterns in co-authorship of scientific papers. As seen here, Canada is an important component of this network. The United States is the clear hub of international scientific collaboration, with particularly strong links to the United Kingdom, Germany, Canada, China, Japan, and France. Even though the United States tends to collaborate less proportionately than other leading countries, the sheer volume of its scientific production in terms of international co-authorship is far greater than other countries (more than double that of the second-ranking United Kingdom).

The United States is the top international collaborator for Canada by a significant margin based on the number of co-publications shared between the two countries. The United Kingdom is also an important source of collaborations for Canadians, but the number of co-authored papers is considerably smaller than with the United States. Canadians also collaborate frequently with colleagues in France, Switzerland, the Netherlands, Australia, and Japan — all leading performers of scientific research. Canada has a notable and growing level of collaboration with researchers in China.



Data source: Calculated by Science-Metrix using Scopus database (Elsevier)

Figure 6.1

Collaboration Network of 20 Leading Countries, 1997–2010

The size of a country's bubble is proportional to its number of international collaborations. The width of a link between two countries is proportional to the number of collaborations between them. To make the figure easier to read, the weakest links have been removed.

Figure 6.2 shows the percentage of a country's total papers that have at least one co-author affiliated with an institution in another country. Canada had an overall collaboration rate of 43 per cent in 2005–2010, seventh highest in the world. In comparison, the top three countries — Switzerland, Sweden, and the Netherlands — all had collaboration rates of around 50 per cent.

One challenge with interpreting data such as those presented in Figure 6.2 is that larger countries tend to collaborate with international colleagues less often, due in part to the fact that researchers in those countries simply have more

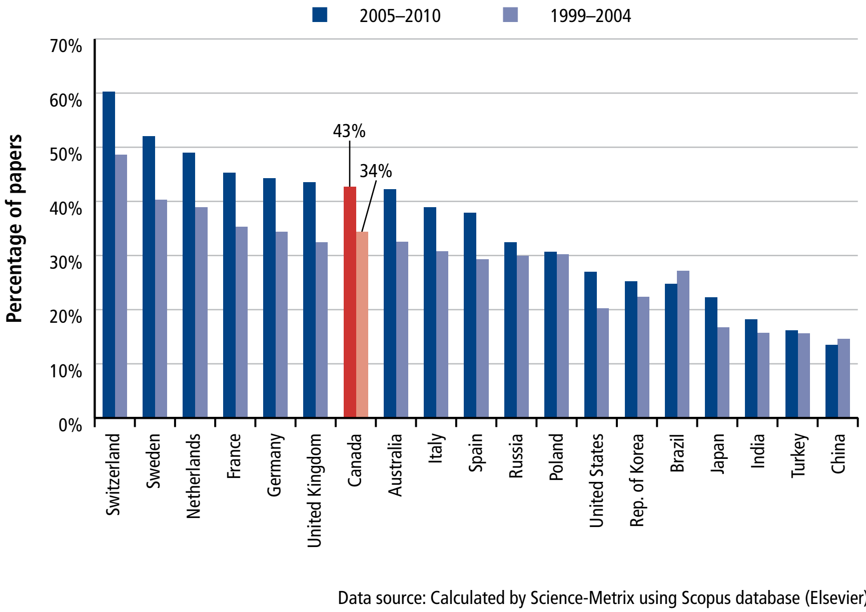


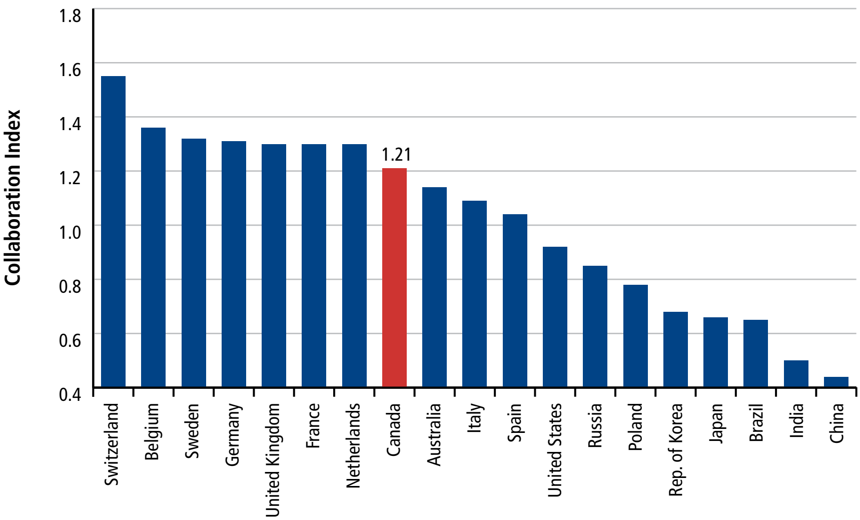
Figure 6.2

Percentage of Scientific Papers Authored with an International Collaborator

Percentages shown are based on whole counts of publications, and are a percentage of the total number of papers for the top 19 countries by total number of papers produced in that sub-field of research.

potential domestic colleagues to work with. As a result, a fair comparison of research collaboration rates across countries should take into account the size of the country (in terms of the number of papers published). Thus the Panel used additional advanced bibliometric techniques to investigate Canada's levels of research collaboration. For example, the Collaboration Index (CI) was used to measure the difference between the observed level of collaboration and the expected level based on the number of papers produced. The overall CI for Canada is 1.21. This indicates that Canadian researchers collaborate with those in other countries approximately 20 per cent more than might be expected based on Canada's number of papers (see Figure 6.3).

Based on a similar approach, the Collaboration Affinity (CA) index was used to assess the collaboration affinity of other countries with Canada. Like the Collaboration Index, this variable is based on the difference between observed and expected numbers of co-authored papers based on the overall size of publication output in respective countries. Canada's Collaboration Affinity towards a country



Data source: Calculated by Science-Metrix using Scopus database (Elsevier)

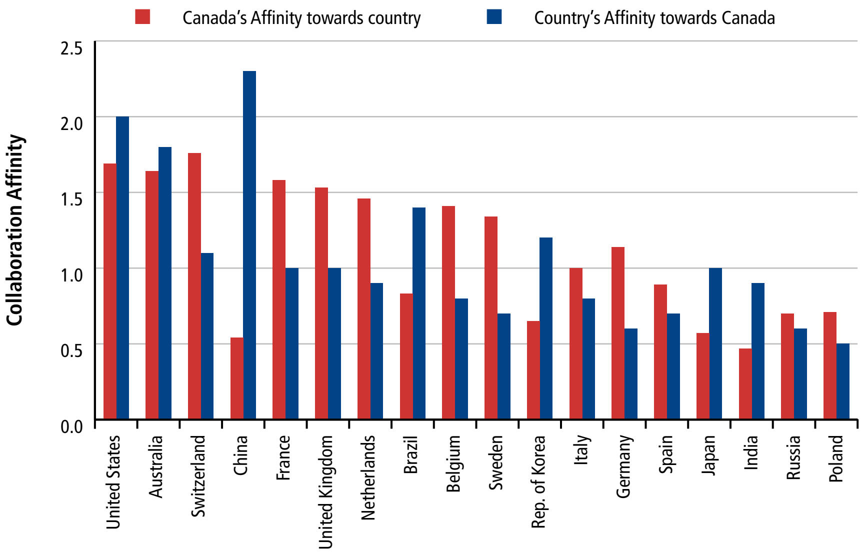
Figure 6.3

Collaboration Index (CI) Scores for Top Scientific Producers, 2005–2010

An index score of 1.0 is equal to the expected level of collaboration based on the number of publications in that country. Scores above 1.0 indicate a higher level of collaboration than expected while scores below 1.0 indicate a lower level of collaboration than expected.

and that country's Collaboration Affinity towards Canada are not necessarily symmetrical. For example, 1,000 co-authored papers could represent a high proportion of country A's total production and result in a high Collaboration Affinity of country A to country B; whereas the same 1,000 co-authored papers could represent only a tiny proportion of country B's production and result in a much lower Collaboration Affinity of B to A. Therefore, although Canadians may exhibit a higher propensity to collaborate with colleagues in a specific country, the reverse may not be the case (see Appendix 1 for additional details on methodology). Similarly, a country may have a strong tendency to collaborate with Canadians, even though the reverse may not always be true.

Figure 6.4 presents the results of this analysis of Collaboration Affinities. It again demonstrates the high level of international collaboration between Canadian researchers and their counterparts in the United States. Canadians, in general, exhibit a high affinity for publishing with co-authors in Switzerland, the United States, Australia, France, and the United Kingdom — all leading countries in scientific research. Countries with a high affinity for publishing with Canadian researchers include the United States, Australia, China, Brazil, and the Republic of Korea. Based on this analysis, Canadians are less likely to collaborate with researchers from China and the Republic of Korea, but researchers from these countries have a high affinity for publishing with Canadians.



Data source: Calculated by Science-Metrix using Scopus database (Elsevier)

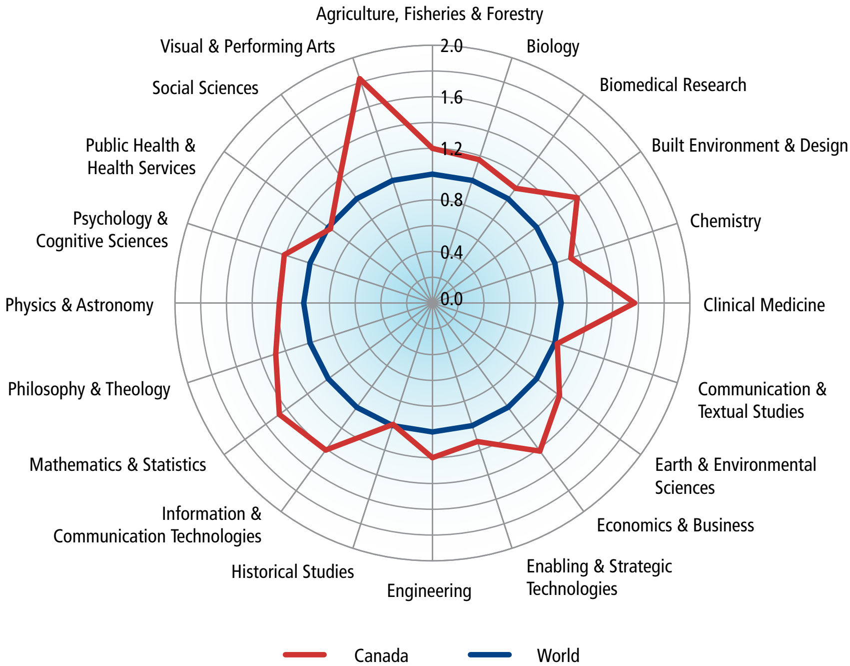
Figure 6.4

Collaboration Affinities (CAs) Between Canada and Other Countries

Collaboration Affinity scores are based on the difference between the expected and observed number of papers with an international co-author based on a regression model, with the score equal to the observed level as a ratio of the expected level. Countries are presented in order of the total of the two Collaboration Affinities, highest to lowest.

International collaboration can also be analyzed at the level of individual research fields. As demonstrated in Figure 6.5, Canadian researchers across nearly all fields co-author with researchers in other countries more than would be expected, with the highest levels of collaboration in Visual and Performing Arts (CI = 1.83) and Clinical Medicine[22] (CI = 1.57). The lowest levels of collaboration are in Communication and Textual Studies, Historical Studies, and Public Health and Health Services, with Collaboration Indices at or slightly below the world level.

22 See Section 2.1 for an explanation of research fields in the context of this assessment. This section also explains that Clinical Medicine and Historical Studies are broader than in some common usages.



Data source: Calculated by Science-Metrix using Scopus database (Elsevier)

Figure 6.5

Collaboration Index (CI) by Field of Research in Canada

This figure is based on a collaboration index (CI) computed from bibliometric data. The CI measures the difference between the observed level of collaboration and an expected level taking into account the overall number of papers in a particular field and country. The blue line indicates the world average of 1.0.

6.3 ANALYZING CLUSTERS OF RELATED RESEARCH ACTIVITY

One of the challenges in any bibliometric analysis is to define a set of field and sub-field categories that accurately reflect the existing patterns of scientific research. In general, bibliometric studies do so by first focusing on traditional discipline categories (e.g., chemistry, physics, history) and then mapping academic journals to these categories. The current assessment, for example, uses the Science-Metrix discipline ontology and journal mapping scheme (as described in Chapter 2) as its basis.

Bibliometricians, however, are currently experimenting with a more sophisticated approach to identifying areas of related research. This approach relies on the use of computational techniques to identify clusters of related research based on citation patterns. For example, a group of papers with a high level of cross-citation (i.e., authors frequently citing each other or the same papers) would be identified as a particular area of research activity. As a result, instead of depending on a previously developed taxonomy of research fields, the structure of scientific research itself, as reflected by citation patterns, determines the research topics that emerge. This technique can be useful in illuminating areas of interdisciplinary research that are often poorly served by traditional field and sub-field categories, and identifying emerging research areas or topics with a high level of specificity (see Klavans & Boyack (2010) for a discussion of this type of approach).

To provide additional insights beyond those of the traditional bibliometric indicators (see Chapter 4), the Panel also commissioned an analysis of research clusters. For this purpose, 86 per cent of the papers in the Scopus database (16.1 million research papers) were grouped into about 48,000 clusters of related research based on patterns in co-citation. Most of the clusters that resulted from this process were relatively small, with 98 per cent containing less than 1,000 papers. Studying all of these clusters is therefore impractical. For this reason, subsequent analysis focused only on clusters with more than 250 Canadian papers. Once all papers were grouped into these clusters of research activity, keywords and frequently used terms in their constituent papers, were used to characterize the nature of the research in that cluster (see Box 6.2 for a discussion of the term "cluster"). The results of this analysis are presented in the following sections.

Box 6.2
Bibliometric Research Clusters Versus Other Types of Research Clusters

In this section of the report, the term "cluster" is used to refer to a group of related research papers. This use stems from the bibliometric literature on these techniques. Clusters, as defined here, merely correspond to a body of research papers closely linked through patterns in citation, and do not necessarily indicate that researchers are working on collaborative projects. The bibliometric use of the word "clusters" is not comparable with the more common use of the term to describe research clusters based on established collaborative partnerships or physical or virtual networks between specific organizations or researchers, such as those created through the federal Networks of Centres of Excellence[23] or the National Research Council's Technology Clusters[24] initiative. However, it is possible that such programs and the actual networks and clusters they support might have a discernible impact on bibliometric clusters through their effect on publication patterns.

23 http://www.nce-rce.gc.ca/index_eng.asp

24 http://www.nrc-cnrc.gc.ca/eng/clusters/index.html

6.3.1 Highly Cited Research Clusters in Canada

Table 6.1 identifies the top 10 clusters of papers by research impact, as reflected by the level of citations (Average Relative Citations) for Canadian research compared with the world average for those clusters. Many of these clusters are in medicine, including clusters related to thrombosis (blood clots), hepatitis, rheumatoid arthritis, *C. difficile* infection, pulmonary disease, kidney transplantation, and acute myocardial infarction (heart attacks). Canada also produces high-impact research in clusters related to cosmology and astrophysics (cluster 4) and high energy lasers (cluster 9).

Table 6.1

Top 10 Research Clusters by Average Relative Citations (ARC)

	Cluster Keywords	ARC	Canada's Share of World Papers (%)
1	Thrombosis, Factor, Venous, Pulmonary, Risk, Heparin, Study, Clinical, Results, Disease	2.56	4.8
2	Hepatitis, Hepatitis B, HBV, B Virus, Infection, Chronic, DNA, Lamivudine, Liver	2.49	2.8
3	Disease, Arthritis, Treatment, Rheumatoid, Psoriasis, Clinical, Inflammatory	2.15	4.6
4	Cosmological, Energy, Universe, Dark Energy, Model, Field, Matter, Background, Gravity	2.15	5.2
5	*Clostridium difficile*, Toxin, Perfringens, Infection, Diarrhoea, Strains, Colitis	2.13	7.2
6	Lung, Sarcoidosis, Disease, Pulmonary, Transplantation, Cell, Fibrosis, Interstitial	2.07	2.9
7	Renal, Blood, Acute, Cardiac, Study, Failure, Care, Shock, Contrast, Pressure, Sepsis	2.03	4.5
8	Transplantation, Renal, Kidney, Graft, Recipients, Survival, Rejection, Pancreas, Sirolimus	2.00	4.5
9	Laser, Femtosecond, Ablation, Pulse, Optical, Surface, High energy, Glass, Beam, Material	1.97	5.0
10	Coronary, Myocardial, Stent, Infarction, Acute, Platelet, Artery, Clinical, Risk, Disease	1.95	5.0

Data source: Calculated by Science-Metrix using Scopus database (Elsevier)

Clusters selected have a minimum of 250 papers published by Canadian researchers (an arbitrary cut-off determined by Science-Metrix). Clusters are ranked in order of decreasing impact as measured by the Average Relative Citations (ARC) for Canadian papers in that cluster. Keywords are listed in order of the frequency in which they appear in papers in that cluster.

6.3.2 Highly Specialized Research Clusters

Cluster analysis was also used to identify areas of research specialization in Canada — i.e., areas in which Canada publishes more than would be expected based on average world publication rates on that topic. Table 6.2 presents the results of this analysis. The research clusters identified here are considerably more diverse than those associated with research impact. Although two research areas of high specialization are also in medicine (neonatal/pediatric pain management, and traumatic brain injury and rehabilitation), Canadian researchers also appear to be highly active in a number of areas related to geology and mineral extraction (clusters 4, 6, 8, and 9), and oil sands (cluster 5, see Spotlight on Oil Sands); and in several areas related to environmental science and toxicology, including environmental mercury deposition (cluster 2), stress impacts in freshwater fish species (cluster 3), and polychlorinated biphenyls (PCBs) in the environment (cluster 7).

Table 6.2

Top 10 Research Clusters by Specialization Index (SI)

	Cluster Keywords	SI	ARC	Canada's Share of World Papers (%)
1	Pain, Children, Study, Neonates, Management, Neonatal, Patients, Scale, Procedures, Assessment, Infant, Analgesia, Pediatric	3.58	1.50	15.5
2	Mercury, Hg, Concentrations, Atmospheric, Snow, Deposition, Emissions, Ozone, Surface, Measurements, Soil, Gaseous, Water	3.41	1.34	14.8
3	Fish, Growth, Levels, Cells, Plasma, Cortisol, Stress, Water, Trout, Gill, IGF, Expression, Hormone, Blood, GH, Rainbow, Ammonia	3.32	1.37	14.4
4	Rocks, Formation, Age, Belt, Be, Ga, Basin, Zone, Neoproterozoic, Complex, Deposits, Crust, Tectonic, Craton, Zircon, Metamorphic	3.28	1.19	14.2
5	Oil, Asphaltene, Crude, Asphalt, Temperature, Properties, Bitumen, Water, Crude oil, Wax, Molecular, Surface, Viscosity, Polymer	3.05	1.31	13.2
6	Gold, Fluid, Deposits, Ore, Quartz, Rocks, Hydrothermal, Mineralization, Inclusions, Mineral, Alteration, Formation, Veins	2.69	1.30	11.6
7	Concentrations, Levels, Samples, PCBs, Polychlorinated, Exposure, Study, Compounds, Congeners, Environmental, Biphenyls, Fish, Soil	2.68	1.49	11.6
8	Mantle, Rocks, Melt, Magma, Isotopic, Composition, Elements, Ratios, Volcanic, Isotope, Source, Basalts, Olivine, Inclusions, Arc, Crust, Lavas	2.59	1.14	11.2
9	Rocks, Basin, Volcanic, Central, Formation, Arc, Subduction, Andes, Cretaceous, Plate, Crustal, Tectonic, Deformation, Fault, Cordillera, Crust	2.54	0.88	11.0

continued on next page

	Cluster Keywords	SI	ARC	Canada's Share of World Papers (%)
10	Injury, Brain, Patients, Traumatic Brain injury, Head, TBI, Study, Rehabilitation, Children, Cognitive, Outcome, Clinical, Concussion, Neuropsychological	2.31	1.32	10.0

Data source: Calculated by Science-Metrix using the Scopus database (Elsevier)

Clusters selected have a minimum of 250 papers published by Canadian researchers (an arbitrary cut-off determined by Science-Metrix). Clusters are ranked by decreasing Specialization Index (SI) for the Canadian papers in that cluster, a measure of the frequency of papers published in that area compared with the world's average. Keywords are listed in order of the frequency in which they appear in papers in that cluster. ARC refers to the Average Relative Citations for Canada.

Spotlight on Oil Sands

Bitumen resources, known as oil sands, are a mixture of sand, water, and bitumen and are located around the globe in locations as diverse as Canada, Venezuela, China, Russia, and Madagascar. These bitumen resources have become an increasingly important source of energy for the world in the last decade and nowhere has there been more development of this supply source than in Alberta, which has three main deposits of oil sands underlying the province. With these resources, Canada is third to Saudi Arabia and Venezuela in proven oil reserves (CIA, 2012).

It has taken a long time and significant innovation for Canada to develop the oil sands. These resources were noted in explorer maps as early as 1778, and in 1819 there was an attempt at a geological description. The first demonstration of the use of oil sands for paving was in 1915, followed by drilling in 1924. However, the most substantive breakthrough came in the 1920s when Dr. Karl Clark at the Alberta Research Council demonstrated that bitumen could be separated from the sand using hot water. At this point it became evident that bitumen could likely be used as a crude oil source. The 1950s discovery that steam injected underground could enable bitumen to flow was another major step in development. The Steam Assisted Gravity Drainage technology first deployed in 1978 through an Underground Test Facility Project, led by the Alberta Oil Sands Technology and Research Authority, was the next significant recovery scheme for bitumen too deep to mine, and its development required strong collaboration between industry, the government, and academia.

Development of the oil sands involves many fields of study, including geology, chemistry, engineering, and biological and social sciences. Today production from the oil sands is 1.5 million barrels per day with an expected growth to 3.7 million barrels per day by 2025. This is expected to contribute $3.1 trillion to the Canadian economy over the next 25 years (CAPP, 2012). This economic impact, however, will be at risk in the absence of innovation that leads to a significantly lower environmental and social footprint.

6.3.3 Rapidly Growing Research Clusters

The research cluster analysis also identified the fastest growing research clusters in Canada and the world — areas in which research output is increasing rapidly based on the Growth Index (GI) (see Chapter 4). As shown in Table 6.3, many of the fastest growing research clusters in Canada in recent years are associated with activity in Information and Communication Technologies (ICT), including networking and wireless technologies, information processing and computation, speech recognition and other biometric technologies, and advanced data analysis techniques. Several rapidly growing clusters are associated with digital media technologies (clusters 2, 4, 13, and 15). Other research and technology areas with rapid rates of growth include nanotechnologies (cluster 3), fuel cells (cluster 6), and space and planetary science and technologies (cluster 10).

Table 6.3

Rapidly Growing Research Clusters

	Cluster Keywords	Growth Index		ARC	Canada's Share of World Papers (%)
		Canada	World		
1	Networks, Sensor, Wireless, Nodes, IEEE, Routing, Energy, System, Mobile, Algorithm, Protocol	11.17	11.48	1.11	4.9
2	User, Design, Interaction, System, Interface, Mobile, Information, Display, Virtual, Model, Applications	7.03	5.60	1.78	7.6
3	Carbon, Nanotubes, Properties, Single, Surface, Electron, Graphene, Field, Temperature, Chemical, Structure, Composite	5.37	3.47	1.17	2.1
4	Information, Web, Model, Network, System, User, Social, Knowledge, Semantic, Algorithm	4.98	4.78	1.07	4.0
5	Channel, Performance, System, Algorithm, IEEE, Frequency, Multiple, Power, Signal, Scheme, Interference	4.90	4.20	1.29	7.0
6	Fuel, Membrane, Fuel Cell, Water, Methanol, Proton, Performance, Pt, Cells, Polymer, Conductivity, Electrochemical	4.38	3.83	1.32	5.7
7	Filter, Frequency, Antenna, Structure, Design, Transmission, Band, Microstrip, Waveguide, Electromagnetic, Photonic, Resonator	4.35	4.20	1.28	5.3
8	Model, Software, System, Web, Service, Information, Language, Development, Framework, Logic, IEEE, Architecture	4.33	4.39	1.22	5.1
9	Speech, Recognition, System, Model, Algorithm, Noise, Speaker, Speech recognition, Signal, IEEE, Adaptative, Acoustic	4.28	3.82	1.40	4.4
10	Mars, Surface, Martian, Lunar, Water, Model, Solar, Ice, Dust, Atmosphere, Venus, Field, Thermal, Earth, Magnetic, Moon, Missions	4.24	1.82	1.10	4.3

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	Cluster Keywords	Growth Index		ARC	Canada's Share of World Papers (%)
		Canada	World		
11	Recognition, Fingerprint, System, Iris, Image, Algorithm, Feature, Biometric, Character, Matching, Identification, Handwritten, Verification	4.13	5.89	1.33	4.0
12	Scheme, Key, Security, Signature, Protocol, Secure, Authentification, Algorithm, Attack, Efficient, Information	4.10	5.38	0.96	4.3
13	Image, Method, Algorithm, Model, System, Recognition, Detection, Video, Segmentation, Analysis, Feature, 3D, Tracking, Face, Motion	3.73	4.41	1.28	3.8
14	Antenna, Bandwidth, Frequency, Design, Patch, Microstrip, Radiation, Band, GHz, Slot, Dual, Impedance, Monopole, Array, Gain	3.51	4.45	0.73	3.6
15	Data, Query, Spatial, System, Database, Algorithm, Processing, GIS, Flash, Web, Applications, Memory, Management	3.42	4.28	1.12	4.8
16	Data, Fuzzy, Algorithm, Model, System, Learning, Classification, Network, Set, Neural, Clustering, Mining, Information, Analysis, Neural network	3.30	4.29	1.21	3.9

Data source: Calculated by Science-Metrix using the Scopus database (Elsevier)

Clusters selected have a minimum of 250 papers published by Canadian researchers (an arbitrary cut-off determined by Science-Metrix). Keywords are listed in order of the frequency in which they appear in papers in that cluster. The Growth Index measures the difference in publication numbers between the periods 2003–2006 and 2007–2010. ARC refers to the Average Relative Citations for Canada.

6.3.4 Interdisciplinary Research Clusters

Bibliometric cluster analysis can be particularly useful in identifying interdisciplinary research clusters by analyzing the references included in the papers in each cluster. Clusters that cite papers in many fields of research (based on traditional field categories such as those used in Chapter 4) are counted as highly interdisciplinary; clusters that cite other research primarily in a single field are less so. A variable called the Interdisciplinarity Score (IS) was used for this aspect of the Panel's research. The IS measures the degree to which references in each cluster are spread over multiple fields.[25]

Table 6.4 presents the results of this analysis, and highlights the 10 most interdisciplinary research clusters in Canada. Many of the clusters identified here are associated with environmental science and toxicology, including wastewater

25 Note that this variable is constructed based on the field categories used in the main body of the assessment, some of which are more closely related than others. For example, papers that cite work in Biomedical Research and Clinical Medicine are counted as equally interdisciplinary as those that cite work in Economics and Business, and Engineering.

treatment technologies (cluster 1); water and soil contamination (clusters 2 and 4); environmental toxicology (particularly with respect to fisheries, cluster 3); environmental remediation technologies (e.g., biosorption of heavy metals, cluster 5); and polychlorinated biphenyls (PCBs) (cluster 9).

In addition, there are several highly interdisciplinary clusters related to the biomedical sciences, such as tissue engineering technologies (cluster 6), liposomes and drug delivery (cluster 8), and colloidal nanoparticles (cluster 10). The research cluster focused on planetary and space science (cluster 7), already identified as one of the most rapidly growing research clusters, is also highly interdisciplinary. The PCB cluster, identified in Section 6.3.2 as highly specialized, is highly interdisciplinary as well. Canada's research contributions in many of these areas are more highly cited than the world average for papers in that area; and Canada is highly specialized in the clusters related to PCBs and wastewater treatment.

Table 6.4

Top 10 Interdisciplinary Research Clusters

	Cluster Keywords	Interdisciplinarity Score (IS)	ARC	Canada's Share of World Papers (%)
1	Water, Concentrations, Treatment, Compounds, Wastewater, Pharmaceuticals, Drinking, Environmental, Organic, Exposure, Antibiotics, Degradation, Removal, pH, Soil, Formation, Extraction, Liquid, Disinfection	0.485	1.11	6.0
2	Arsenic, Surface, pH, Adsorption, Iron, Water, Reduction, Sorption, Removal, Soil, Fe, Concentrations, Solution, Conditions, Groundwater, Phosphate, Metal, Acid, Chemical, Species, Oxidation	0.446	1.21	4.3
3	Concentrations, Effects, Exposure, Fish, Toxicity, Water, Levels, Study, Activity, Species, Metal, Environmental, Cells, Sediment, Compounds, Treatment, Endocrine, Growth, Liver	0.443	1.34	7.1
4	Plants, Soil, Cd, Metal, Concentrations, Growth, Heavy, Zn, Be, Accumulation, Uptake, Pb, Species, Root, Mg, Cadmium, Arsenic, Cu, Phytoremediation, Acid, Heavy Metals	0.432	1.18	3.6
5	Adsorption, Removal, pH, Metal, Ions, Activated, Carbon, Solution, Sorption, Concentration, Aqueous, Water, Capacity, Process, Ion, Surface, Acid, Biosorption, Activated Carbon, Equilibrium, Langmuir, Isotherm	0.432	0.97	2.1
6	Cell, Surface, Tissue, Polymer, Properties, Hydrogels, Acid, Scaffolds, Water, Engineering, Protein, Bone, Nerve, Tissue Engineering, Materials, Temperature, Adhesion, Swelling, Drug, Adsorption, Collagen	0.430	0.97	3.0

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	Cluster Keywords	Interdisciplinarity Score (IS)	ARC	Canada's Share of World Papers (%)
7	Mars, Surface, Martian, Lunar, Water, Model, Solar, Ice, Dust, Atmosphere, Venus, Field, Thermal, Earth, Magnetic, Moon, Missions	0.412	1.10	4.3
8	Gene, Liposomes, Drug, Transfection, Cell, Cationic, Expression, Complexes, Efficiency, Gene Delivery, Lipid, Tumor, Plasmid, *In Vivo*, Therapy, Nanoparticles, Protein, Micelles, *In Vitro*, Acid, Peptide	0.404	1.28	4.6
9	Concentrations, Levels, Samples, PCBs, Polychlorinated, Exposure, Study, Compounds, Congeners, Environmental, Biphenyls, Fish, Soil, Pesticides	0.402	1.49	11.6
10	Films, Surface, Layer, Particles, Colloidal, Photonic, Polyelectrolyte, Adsorption, Crystal, Multilayer, Polymer, Structure, Silica, Optical, Layer-by-layer, Deposition, Method, pH, Spheres, Nanoparticles, Multilayers	0.399	1.52	2.6

Data source: Calculated by Science-Metrix using the Scopus database (Elsevier)

Clusters selected have a minimum of 250 papers published by Canadian researchers (an arbitrary cut-off determined by Science-Metrix). Keywords are listed in order of the frequency in which they appear in papers in that cluster. The Interdisciplinarity Score (IS) measures the degree to which references in each cluster are spread over multiple fields, the maximum theoretical value is 1.0. ARC refers to the Average Relative Citations for Canada.

6.4 EMERGING RESEARCH AREAS IDENTIFIED BY CANADIAN S&T EXPERTS

In addition to identifying emerging and interdisciplinary research clusters from the bottom-up, the views of Canadian S&T experts were obtained on emerging research areas and technologies. In the survey of Canadian S&T experts, respondents were asked to identify areas of research or technological applications that are likely to be of increasing significance over the next 10 to 15 years, and where Canada is best placed to be among the leaders in development and/or application. Each respondent had the opportunity to identify up to five areas.

As shown in Figure 6.6, the most frequently identified areas by the almost 700 respondents were related to health (see Spotlight on Canadian Stem Cell Research), energy technologies, and digital media.

For purposes of comparison, Figure 6.6 also shows a summary of survey responses from the 2006 S&T report. The views of Canadian S&T experts have not changed much since 2006: energy and health/biomedical technologies continue to be identified as areas in which Canada is well positioned to become a global leader.

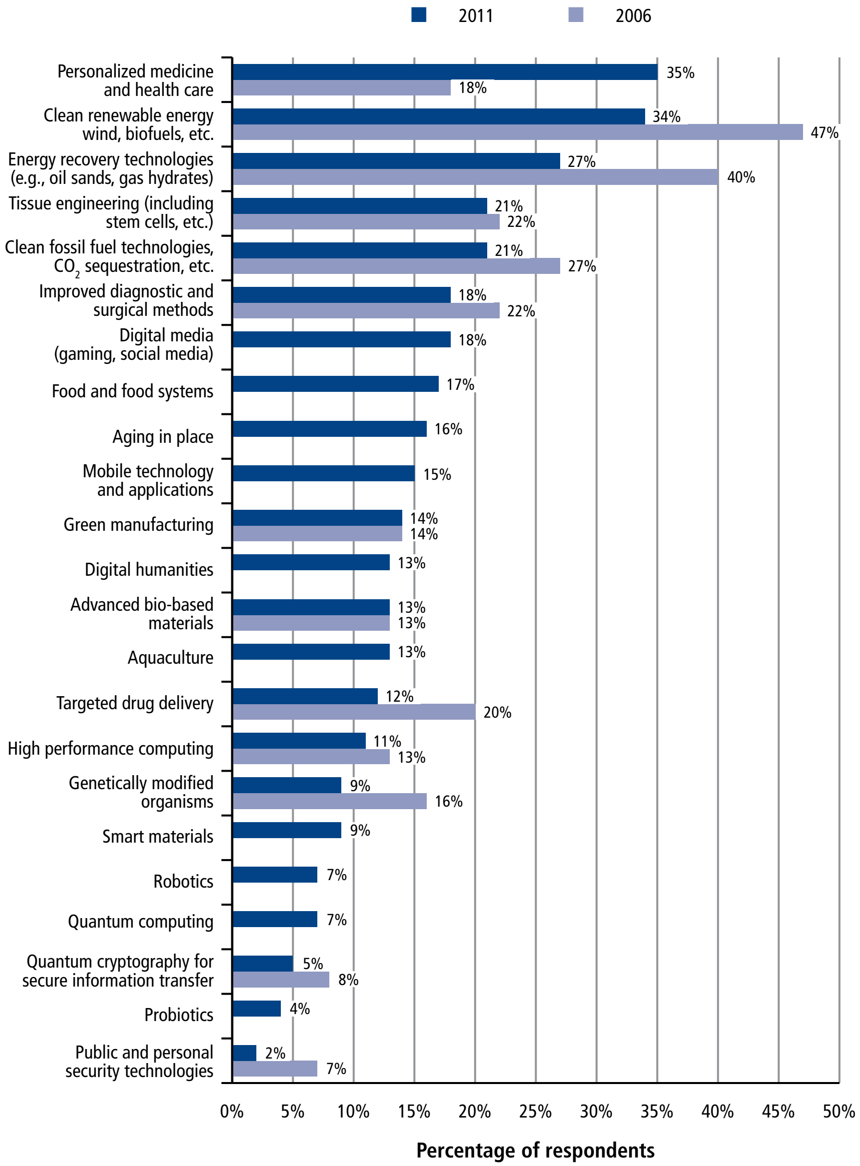


Figure 6.6

Emerging S&T Areas Where Canada is Positioned to be a Global Leader According to the Survey of Canadian S&T Experts

This figure shows the percentage of respondents identifying each area as emerging areas of S&T where Canada is well positioned to be a global leader. The total is over 100 per cent as respondents were asked to identify the top five areas. Data is shown for the 2011 survey and for the 2006 survey (see CCA, 2006), where available.

The most significant changes since 2006 are a higher rate of identification of personalized medicine and health care as emerging areas in 2011, and a lower rate of identification of energy technologies.

Spotlight on Canadian Stem Cell Research

Stem cells were discovered by two Canadian researchers, Dr. James Till and the late Dr. Ernest McCulloch, at the University of Toronto over 50 years ago. This great Canadian contribution to medicine laid the foundation for all stem cell research, and put Canada firmly at the forefront of this field, an international leadership position that is still maintained.

Stem cell research, which is increasingly important to the future of cell replacement therapy for diseased or damaged tissues, spans many disciplines. These disciplines include biology, genetics, bioengineering, social sciences, ethics and law, chemical biology, and bioinformatics. The research aims to understand the mechanisms that govern stem cell behaviour, particularly as it relates to disease development and ultimately treatments or cures.

Stem cell researchers in Canada have a strong history of collaboration that has been supported and strengthened since 2001 by the Stem Cell Network (SCN) (one of the federal Networks of Centres of Excellence), a network considered to be a world leader in the field. Grants awarded through the SCN alone have affected the work of more than 125 principal investigators working in 30 institutions from Halifax to Vancouver. Particularly noteworthy institutions include the Terry Fox Laboratory at the BC Cancer Agency; the Hotchkiss Brain Institute in Calgary; Toronto's Hospital for Sick Children, Mount Sinai Hospital, University Health Network, and the University of Toronto; the Sprott Centre for Stem Cell Research in Ottawa; and the Institute for Research in Immunology and Cancer in Montréal. In 2010, a new Centre for the Commercialization of Regenerative Medicine was formed to further support stem cell initiatives of interest to industry partners.

Today, Canadian researchers are among the most influential in the stem cell and regenerative medicine field. SCN investigators have published nearly 1,000 papers since 2001 in areas such as cancer stem cells; the endogenous repair of heart, muscle, and neural systems; the expansion of blood stem cells for the treatment of a variety of blood-borne diseases; the development of biomaterials for the delivery and support of cellular structures to replace damaged tissues; the direct conversion of skin stem cells to blood; the evolutionary analysis of leukemia stem cells; the identification of pancreatic stem cells; and the isolation of multipotent blood stem cells capable of forming all cells in the human blood system.

6.5 CONCLUSIONS

Advanced bibliometric techniques enable the study of patterns of collaboration and research clusters. Although these techniques are not as widely used as the more traditional bibliometric indicators presented in Chapter 4, they provide interesting insights on Canada's S&T strengths. Canadian researchers are collaborating with researchers in other countries more than would be expected based on the number of papers produced, and the proportion of papers written with an international collaborator is growing. More importantly, Canadian researchers routinely collaborate with colleagues in other leading S&T countries, including the United States, Germany, Japan, France, and the United Kingdom. It is also a positive sign that China — quickly emerging as a major producer of scientific research — has a high collaboration affinity with Canada. Based on these collaboration patterns, it can be concluded that Canada is well positioned internationally in world-leading science and technology.

The bibliometric cluster analysis provides a more nuanced picture of Canada's research activity. This type of analysis, unconstrained by traditional definitions of research fields, is more able to accurately identify areas of interdisciplinary research. There is a strong concordance between the cluster analysis and the results that emerged from the traditional bibliometric indicators. For example, Canadian research in clusters associated with medical sciences and physics is highly cited compared to world averages. This finding closely matches the results reported in Chapter 4: Canada ranks highest in the world in several sub-fields of Clinical Medicine, Biomedical Sciences, and Physics and Astronomy. Similarly, the areas of comparatively high research output in Canada identified by cluster analysis (Geology, Natural Resources, and Environmental Sciences) align with the findings in Chapter 4. The similarity among the types of research that emerge as high impact or highly specialized in both traditional bibliometrics and in the cluster analysis gives support to the classification system on which this report is based. Although not capturing all the nuances of Canadian research, the top-down approach based on fields and sub-fields does identify broadly the same areas of excellence as the bottom-up analysis of research clusters. However, the cluster analysis may not capture clusters in the humanities, arts, and social sciences because of the lower number of papers in these fields.

Similar patterns emerge from a comparison of the views of Canadian S&T experts on emerging areas with the results of the bibliometric analysis. Canadians identify personalized medicine and health care as an emerging area of strength. Although this precise area is not captured by bibliometrics, Canadian research strength in Clinical Medicine and Biomedical Research clearly emerges from the bibliometric evidence. Similarly, Canada's strength in energy and energy recovery technologies, ranked third by Canadians as an area of potential global leadership, is reflected in the research cluster related to oil sands. In contrast, bibliometric analysis suggests that many of the fastest emerging clusters in Canada are associated with ICT and digital media, yet respondents to the Canadian survey did not identify this area as an emerging Canadian strength.

Although most of the techniques used in this chapter are exploratory, they complement other methodologies used in the report to provide a broad picture of Canada's S&T strengths.

7

Patents and Related Measures

- International Comparisons of Triadic Patents
- Technometric Analysis of USPTO Data
- Comparison with the 2006 Report
- Other Measures of Research Commercialization and Technology Development
- Conclusions

7 Patents and Related Measures

Key Findings

- Canada produces approximately 4 per cent of the world's output of scientific publications, but accounts for only 1.7 per cent of patents. Canada compares relatively poorly to other major countries in terms of patents per capita and royalty and licensing fees from Canadian intellectual property (IP).
- Canadian patent holders accounted for approximately 18,000 patents registered with the USPTO (United States Patent and Trademark Office) during the 2005–2010 period. Canada is one of only three countries with levels of patent citation above the world average in this database.
- Canadian patents in the areas of AgriFood, Chemicals, and Information and Communication Technologies (ICT) are highly cited, indicating considerable impact in the development of related technologies.
- Patents reflect only one aspect of the range of activity involved in research commercialization and technology development. Other indicators used in analyzing this element of S&T, however, are not typically broken down by field of research or are available for only specific institutional settings. This is a gap in Canadian data collection relating to technology development and commercialization.

Traditional divisions of S&T into pure and applied are often considered outdated, as most research is either performed with a commercial or social application as an objective in the short or longer term, or finds such applications even when not envisioned at the time the research was performed. This chapter, however, explores strengths in areas of S&T where application of research and the development of new technologies are the primary aim.

One measure routinely used internationally to compare S&T outputs across countries is patent data. The analysis in this chapter covers all Canadian patent activity, including that which occurs within academic and government contexts and within the private sector.[26] In particular, provincial research organizations and the federal National Research Council are very engaged in technology development and research commercialization, but the data do not separate out these contributions. Moreover, technology development is an area of activity in which collaboration between industry, academic, and government researchers is critical. Industry now funds nearly one billion dollars of research in Canadian universities and colleges annually (Statistics Canada, 2012a), with much of this

26 A detailed assessment of technology development in the private sector is being conducted by the Council's Expert Panel on the State of Industrial Research and Development in Canada.

support focused on research related to the development of specific types of technologies. As a result, while the patent data presented here are very relevant to Canada's academic S&T strengths, the data likely have even greater implications regarding research commercialization and technology development in other sectors.

As the most robust measure available to the Panel, patents form the bulk of the analysis. As described in Chapter 2, however, as a measure of applied S&T and technology development, patents have a number of limitations. Therefore, to provide a more comprehensive picture of Canada's S&T strengths, supplementary evidence is also presented.

Box 7.1
Technometric Indicators Used in this Study

Number of Patents: This indicator refers to the number of patents registered with the United States Patent and Trademark Office (USPTO). Patents are recorded here by the address of the assignee (i.e., patent holder), rather than the inventor.

Specialization Index (SI): This indicator is a measure of Canada's concentration of IP in a particular area of technology development relative to other countries. The patent SI indicator is calculated in an analogous way to that of the bibliometric analysis (see Box 4.1). An SI score greater than 1.0 indicates that Canada (or a province) holds more patents in that area than would be expected based on comparison with other countries.

Average Relative Citations (ARC): ARC here is a measure of the frequency with which patents are cited. ARC for patents is constructed in an analogous way to the ARC indicator for publications (see Box 4.1). An ARC score greater than 1.0 indicates that Canadian patents are more highly cited than the world average for that area (all ARC scores are normalized by technology area).

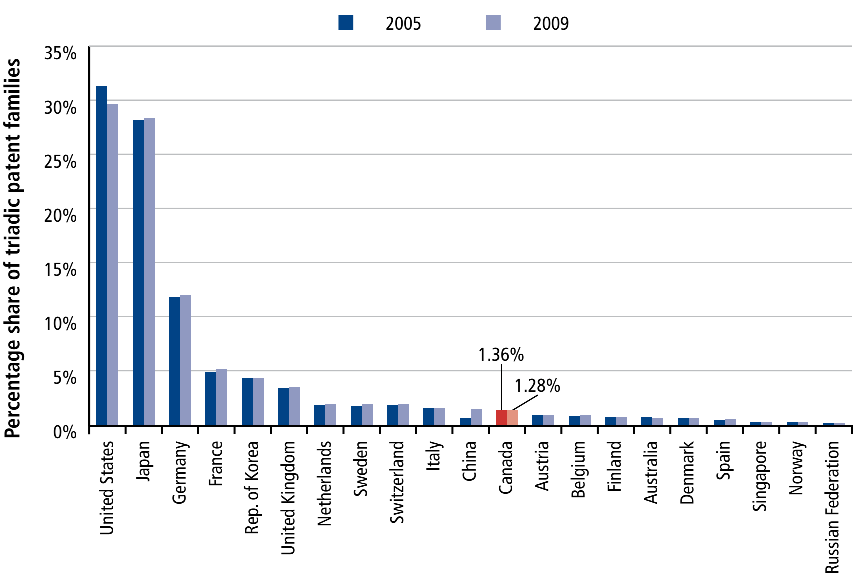
IP Flow: IP flow is an indicator that was developed to assess cross-border flows of intellectual property. It measures the difference between the number of patents developed within a particular region (based on the address of the inventor) and the number of patents currently registered or owned within that region (based on the address of the assignee). Regions with negative IP flow hold the rights to fewer patents than they have invented (i.e., are net *exporters* of patents); while those with a positive IP flow hold the rights to more patents than they have invented (i.e., are net *importers* of patents).

For a more detailed explanation of methods used in calculating these indicators, see Appendix 1.

7.1 INTERNATIONAL COMPARISONS OF TRIADIC PATENTS

Many Canadian and international reports have presented general cross-country comparisons of patent statistics in the context of analyzing S&T performance (e.g., STIC, 2009, 2011; Canadian International Council, 2011; OECD, 2008). As a result, the Panel has not sought to reproduce much of that analysis in this report. The overriding message that emerges from most of these assessments is that business enterprise expenditure on R&D (BERD) (see Chapter 3) is correlated with patent activity, and countries with low BERD, such as Canada, typically have a level of patent activity that is relatively low compared to other leading S&T countries (e.g., BIS, 2011). This finding is generally consistent with the Panel's review of the evidence.

A comparison of Canada's patent stock with its research paper output, for example, shows that while Canada accounts for over 4 per cent of the world's total scientific publications (see Chapter 4), in 2009 it accounted for only 1.28 per cent of the total world stock triadic patent families (sets of patents filed with the European Patent Office (EPO), the U.S. Patent and Trademark Office (USPTO), and the Japan Patent Office (JPO)) (see Figure 7.1). Moreover, Canada's overall share of

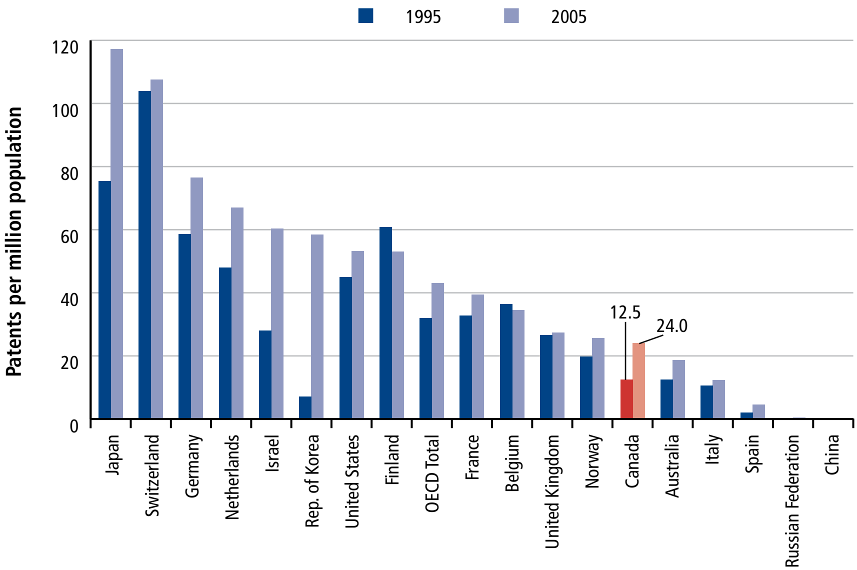


Data source: OECD (2010). *Main Science and Technology Indicators*

Figure 7.1

Percentage Share of Patents in Triadic Patent Families for Selected Countries

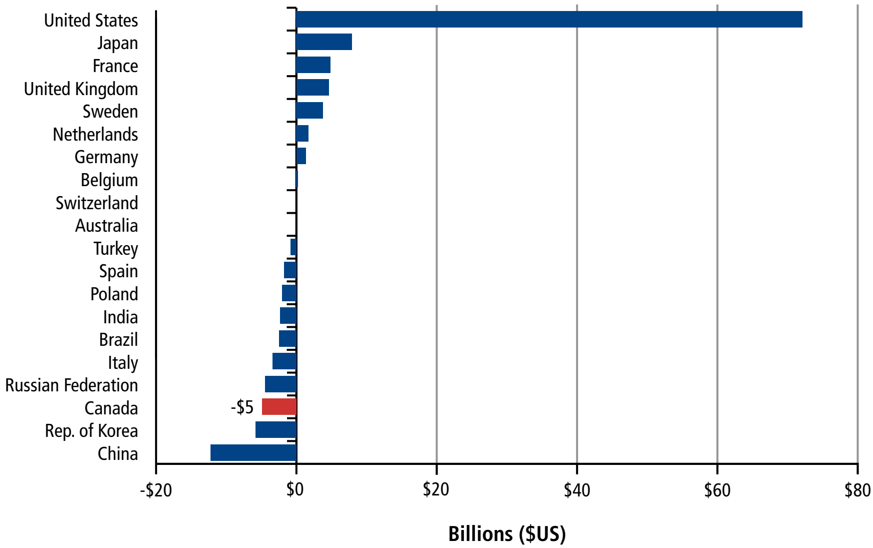
world patents has fallen since 2005. The United States' share of total patents has also declined, but many other developed countries — including Germany, France, Sweden, Japan, and the United Kingdom — increased their share of world patents over the same period. China had the largest increase, which rose from just over half of 1 per cent in 2005 to 1.4 per cent in 2009. Canada also ranks poorly in patents on a per capita basis, with a level that is well below the OECD average (see Figure 7.2).



Data source: OECD (2008). *Compendium of Patent Statistics*

Figure 7.2
Triadic Patent Families per Million Population

Canada also lags in royalties and licensing fees related to intellectual property (IP). In fact, Canada has a net negative balance of nearly five billion dollars in royalties and licensing revenue (Figure 7.3), representing the difference between fees paid to access IP in other countries and the revenue received for access to IP held by Canadians. In comparison, many other leading countries in scientific research (including the United States, Japan, France, Sweden, the United Kingdom, and the Netherlands) have a positive balance with respect to these payments.



Note: Royalty and licence fees are payments for the authorized use of intangible, nonproduced, nonfinancial assets and proprietary rights (such as patents, copyrights, trademarks, industrial processes, and franchises) and for the use, through licensing agreements, of produced originals of prototypes (such as films and manuscripts). Data are in 2010 U.S. dollars.

Data source: The World Bank (2012). World Development Indicators

Figure 7.3
Net Royalty and Licence Fees by Country, 2010

7.2 TECHNOMETRIC ANALYSIS OF USPTO DATA

Building on the Council's first assessment of S&T in Canada in 2006, the Panel undertook a comprehensive analysis of Canadian and world patents using data from the USPTO, the most important patent and trademark office for Canadian patent filers (see Chapter 2).

Not surprisingly, the United States accounts for the largest share by far of the total number of patents registered with the USPTO, being involved in the publication of more than half of the approximately one million patents indexed in the USPTO database in 2005–2010 (see Table 7.1). Japan ranks second with approximately 218,000 patents. In comparison, Canada accounted for about 18,000 patents in the same period. This amounted to 1.7 per cent of the world total.[27] Patent holdings with the USPTO have declined in recent years in many of the leading countries, including Canada, Sweden, Germany, the United Kingdom, France, and Italy.

27 The difference between Canada's share of world patents reported here and that shown in Figure 7.1 is due to the fact that these data are based solely on patents filed with the USPTO, whereas that figure was based on triadic patent families, i.e., sets of patents filed at the USPTO, JPO, and EPO.

In comparison, patent holdings of several Asian countries, including China, the Republic of Korea, and Singapore, increased substantially over the same period.

Table 7.1

USPTO Patent Data for Selected Countries

	2005–2010		1999–2004		
	# of Patents	ARC	# of Patents	ARC	Flow of IP
United States	526,367	1.16	526,732	1.13	0.04
Canada	17,781	1.03	19,210	0.97	-0.19
Israel	5,324	1.00	4,245	0.90	-0.32
Sweden	7,955	0.89	9,266	0.83	0.14
China	47,787	0.88	33,424	1.00	-0.02
Japan	217,949	0.88	201,575	0.93	0.02
Switzerland	10,013	0.86	9,706	0.70	0.38
Australia	6,656	0.81	4,075	0.83	-0.17
Denmark	2,507	0.81	2,674	0.67	-0.15
Finland	6,342	0.81	5,114	0.91	0.18
Rep. of Korea	44,971	0.80	22,483	0.82	0.01
Singapore	3,401	0.80	1,410	1.16	0.29
United Kingdom	12,754	0.79	14,881	0.77	-0.40
Belgium	2,719	0.68	2,920	0.73	-0.29
Netherlands	13,630	0.68	9,407	0.69	0.49
Germany	55,179	0.66	60,064	0.71	-0.07
Italy	6,794	0.63	8,241	0.61	-0.23
France	18,481	0.62	21,134	0.67	-0.11
World	1,023,399	1.00	974,765	1.00	0.00

Note: Number of patents is expressed in full counts. Flow of IP is for 1997–2010. Countries are ranked by ARC for 2005–2010.
Data source: Calculated by Science-Metrix using data from the United States Patent and Trademark Office (USPTO)

Patent citations (captured in Table 7.1 using the Average Relative Citations (ARC) variable) can also be used to gauge the relative importance of patent holdings across countries and patent classes. With this measure, Canada does comparatively well. Canada ranks second, behind the United States, in terms of citations of national patents. Canada is one of only three countries with a level of patent citations above the world average. Canada's overall level of patent citations has also improved modestly in recent years.

The variable presented in the last column in Table 7.1 is also a useful indicator related to Canada's patent stock. This "flow of IP" indicator is based on the difference between the number of patents that originate within a country and the number of patents owned by that country. It essentially captures the degree to which countries are importers or exporters of patents. Canada has an overall negative flow of IP, indicating that Canadians own the IP rights on fewer inventions than they have actually created. This suggests that the purchase of Canadian IP is attractive internationally. In comparison, many other countries are in the process of acquiring IP from abroad as well as creating it. For example, the Netherlands and Switzerland have large, positive IP flow scores, showing a stock of IP ownership in excess of what would be expected based on domestic invention. The United States and Japan also have small, positive IP flow scores, implying that they continue to accumulate more IP than they invent, despite already being world leaders in IP ownership.

Patent data from the USPTO can also be used to identify particular patent classes in which Canada excels compared to other countries. Table 7.2 provides data on key patent indicators for specific technology areas, using the patent classification system developed for the analysis of patents in the Council's 2006 assessment. As shown, Canada ranks first in the world in citations in patents related to AgriFood technologies, indicating that Canadian patents in this area have a high impact on technologies developed around the world. Likewise, Canadian patents are

Table 7.2

Technometric Indicators for Canada by Patent Classification

		2005–2010			1999–2004		
	ARC Rank (2005–2010)	# of Patents	ARC	SI	# of Patents	ARC	SI
AgriFood	1	366	1.61	1.35	536	0.96	1.33
ICT	3	7,775	1.22	0.83	6,223	1.20	0.83
Chemical	2	1,411	1.15	0.89	1,945	0.80	0.83
Mechanical	6	2,130	0.92	1.30	2,898	0.87	1.16
Engineering	5	1,067	0.84	2.20	1,306	0.83	1.85
Electrical	9	630	0.82	0.59	603	0.93	0.52
Transport	6	1,182	0.79	1.66	1,366	0.93	1.42
Human Necessities	8	2,569	0.76	1.19	3,587	0.86	1.21
Energy	11	349	0.70	1.42	303	0.80	1.17
Metals	10	302	0.69	1.16	443	0.92	1.17
All Fields	**2**	**17,781**	**1.03**	**1.00**	**19,210**	**0.97**	**1.00**

Data source: Calculated by Science-Metrix using data from the United States Patent and Trademark Office (USPTO)

This table is ranked by Average Relative Citations (ARC) (2005–2010). The number of patents is expressed here in whole counts. ARC rank shows Canada's rank among the top 19 countries for the 2005–2010 period by number of patents in each class.

highly cited in the fields of Chemicals (ranked second) and Information and Communication Technologies (ICT) (ranked third). These areas, however, do not necessarily correspond to fields of technology development in which Canada is highly specialized. For example, as in most countries, by far the largest share of Canadian patents is associated with applications in ICT (see Spotlight on ICT). Canada's share of patents in ICT, however, is actually lower than what might be expected based on the world average, as indicated by its Specialization Index (SI) score. Areas of technology where Canada is highly specialized include Engineering (SI = 2.20); Transport (SI = 1.66); Energy (SI = 1.42); and AgriFood (SI = 1.35).

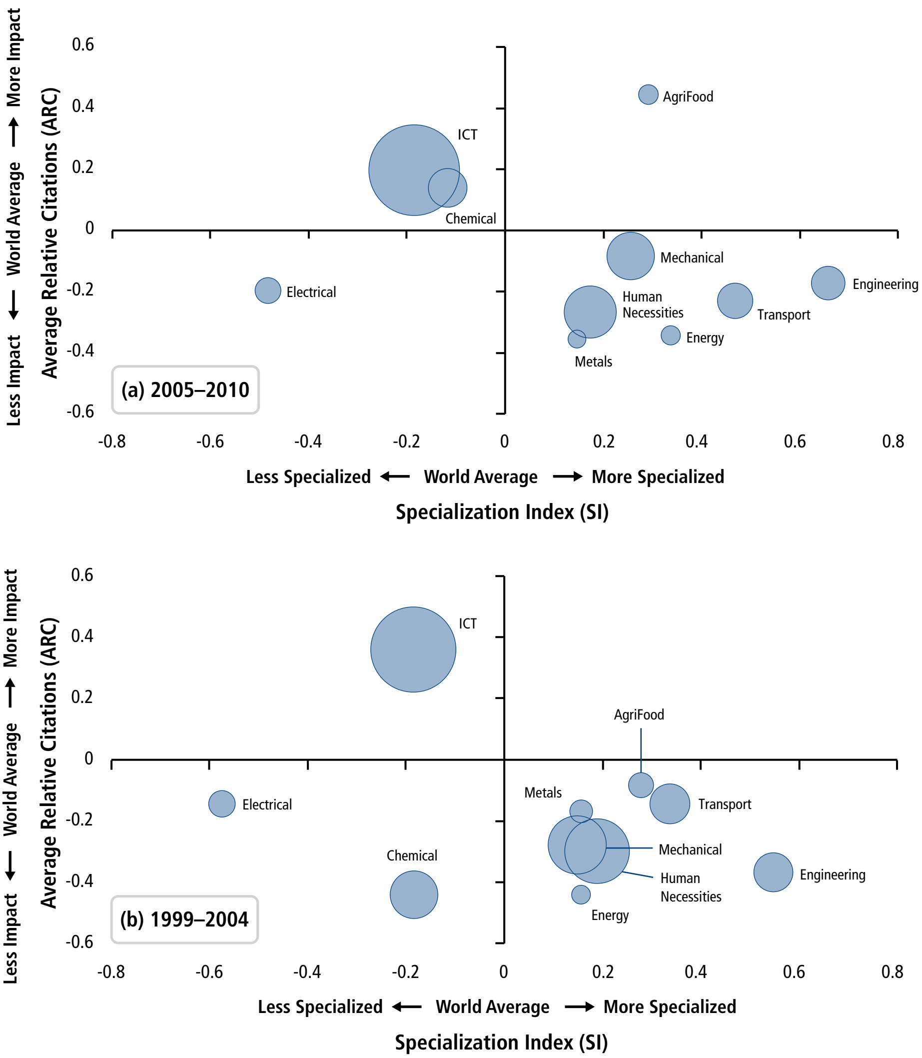
Spotlight on Information and Communication Technologies (ICT)

The Information and Communication Technologies sector encompasses telecommunications, computer networks, information technology, and broadcast media. Canada has made substantial contributions to the field. Historical breakthroughs include Alexander Graham Bell's invention of the telephone and reception of the first transatlantic wireless communication at Signal Hill in St. John's, Newfoundland and Labrador in 1901. Other outstanding contributions by Canadian researchers include amplitude modulation (AM) (1906), the television camera (1934), the pager (1949), as well as more recent innovations by homegrown flagship companies including Nortel Networks Corporation, Research in Motion (RIM), OpenText, and the other 32,700 ICT firms that invested $4.9 billion in research and development in 2010 (Industry Canada, 2011a). Canada has also been an early technology adopter; for example, Canada was the third country in the world to launch a communications satellite (Alouette 1, in 1962).

Canada's geographic size, with a population spanning a distance of over 9,300 kilometres, has served as an impetus for its success and development in the ICT sector. Particularly noteworthy infrastructure that has been developed includes the Communications Research Centre Canada, a centre of excellence providing laboratory services for ICT. The National Research Council also has two institutes supporting ICT: the Canadian Photonics Fabrication Centre and the Institute for Information Technology. CANARIE Inc. connects Canadian researchers with a network of 19,000 kilometres of fibre optic cables. TRLabs is an ICT research consortium that includes industry, academic, and government partners.

Canada's ICT sector is facing challenges as evidenced by the difficulties at ICT flagships Nortel and RIM, and concerns about a number of Canadian ICT companies and technologies being acquired by foreign owners. The ICT hardware manufacturing sub-sector has been in a steady decline and some question if Canada will be able to sustain a leading role in the digital economy as the focus shifts to issues like cloud computing and e-security.

Figure 7.4 shows a positional analysis of Canada's performance related to these areas of technology. This figure is equivalent to Figure 4.6, which was presented in the discussion of the bibliometric evidence. The top-right quadrant contains



Data source: Calculated by Science-Metrix using data from the United States Patent and Trademark Office (USPTO).

Figure 7.4

Positional Analysis of Canada in 10 Fields of the Patent Classification in (a) 2005–2010, and (b) 1999–2004

The size of the bubble is proportional to the number of patents in that field. Zero is equal to the world average for both axes.

patent classes where Canada has a high number of patents relative to other countries and those patents are relatively highly cited. These represent areas of technological strength in Canada (as reflected by patent holdings). The top-left quadrant indicates areas where Canadian patents are highly cited (i.e., have high impact), but where Canada has fewer patents than might be expected based on the world average. As with the bibliometric figures, this quadrant can be interpreted as capturing areas of opportunity for Canada. The bottom-left quadrant contains those classes where Canada has both low levels of impact and low levels of output; and the bottom-right quadrant contains classes where Canada has a relatively high number of patents, but the patents are less cited than the world average. The size of the bubble indicates the overall number of Canadian patents in that area.

Unlike the bibliometric positional analyses, Canada's overall performance in many patent classes is below the world average for these indicators. Only one patent class in Canada, AgriFood, appears in the top-right quadrant in 2005–2010. Two other patent classes, ICT and Chemicals, show levels of impact (as reflected by patent citations) above the world average. The remainder of Canadian patent classes have lower levels of impact than the world average for their classes. In addition, many of these appear in the bottom-right quadrant, which indicates they are areas where Canada has a relatively high number of patents, but with comparatively low levels of citation.

Figure 7.4 also demonstrates trends in these scores over the past decade. For example, two areas of Canadian patenting activity — Chemicals and AgriFood — increased their ARC scores between the two periods. Other fields, however, such as Transport, Energy, Electrical, and Metals, had decreases in patent citations. In general, the levels of specialization associated with these classes did not exhibit large changes between the two periods.

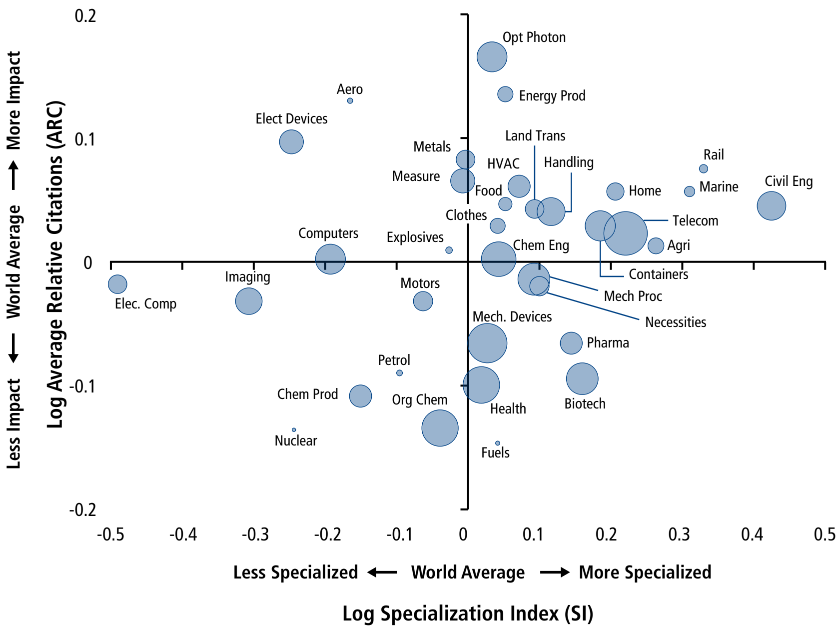
7.3 COMPARISON WITH THE 2006 REPORT

The assessment of Canada's patent data presented in Section 7.2 is in most ways directly comparable to that carried out for the 2006 report. Data were drawn from the same source (i.e., the USPTO), and the same technological categories and patent classes were used in the analysis. The same variables were also used (i.e., the number of patents, ARC), although this analysis added an indicator to measure the flow of patents between jurisdictions.

A comparison of the results at the level of sub-classes with those from the 2006 study reveals some interesting trends (see Figures 7.5 and 7.6). As demonstrated, there have been some large changes in Canada's performance. For example, there were substantial improvements in the ARC scores of Canadian patents in

Agriculture and Organic Chemistry, coupled with a small decrease in their level of specialization. This implies that Canadian patents in these areas are now having greater impact on new technologies while, at the same time, the proportion of Canadian patent activity in this area is declining. Canada's telecom patents also had a modest increase in their ARC score.

In contrast, some areas of Canadian technology had dramatic reductions in their ARC scores since the 2006 report. The most notable of these is Optics and Photonics. Canadian patents in this area were highly cited in the earlier period compared to the world average, but have dropped to just above the world average in 2005–2010. The ARC scores of Energy Production and Distribution, and Metals and Metallurgy, also declined significantly, moving from above the world average to below the world average. In general, more Canadian patent classes now have levels of citation below the world average, implying a decline in the overall relevance of these patents to developing new technologies.

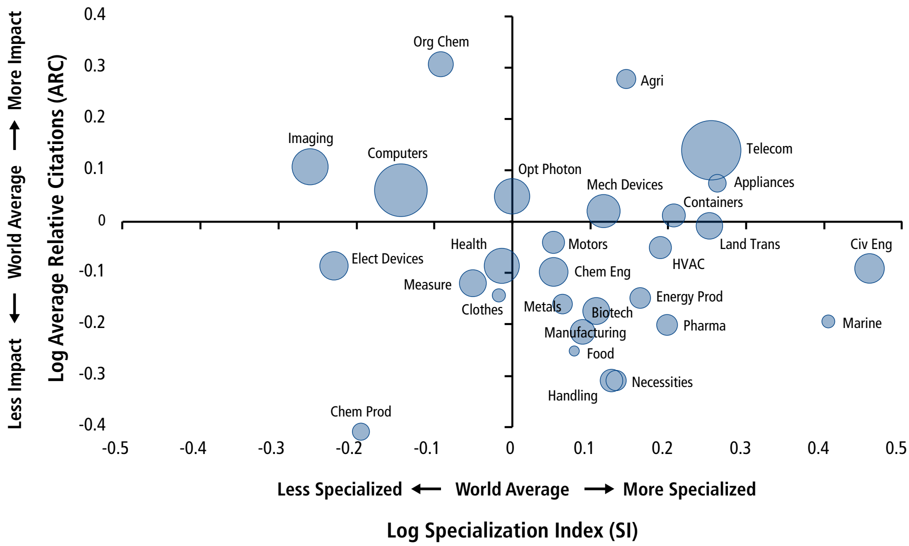


Data source: CCA, 2006

Figure 7.5

Technometric Analysis from the 2006 State of S&T Report

The size of the bubble is proportional to the number of patents in that field. Zero is equal to the world average for both axes.



Note: ARC and SI scores are shown in Log form for patent sub-classes for the purposes of comparison to the 2006 State of S&T report.
Data source: Calculated by Science-Metrix using data from the United States Patent and Trademark Office (USPTO)

Figure 7.6

Technometric Analysis, 2005–2010

The size of the bubble is proportional to the number of patents in that field. Zero is equal to the world average for both axes.

7.4 OTHER MEASURES OF RESEARCH COMMERCIALIZATION AND TECHNOLOGY DEVELOPMENT

Recognizing the limitations of patents in describing the full range of research activities related to technology development, the Panel also explored various other indicators and data sources that could be used to inform its assessment of applied R&D strengths. There are many potential measures of this type, including invention disclosures, royalty and licensing revenue, spin-offs, marketing of new products or services, and university-business (or college-business) partnerships. In some cases market data, such as export data related to certain technologies or sectors, can also be informative about applied S&T strengths. Since this type of metric reflects primarily commercial rather than academic activity, it is beyond the mandate of this Panel.

Statistics Canada's Survey of Intellectual Property Commercialization in the Higher Education Sector (2010) collects data related to IP development in universities and colleges, including royalty and licensing revenues, invention disclosures, patent applications and issues, and personnel involved in IP commercialization and management. The latest figures from this survey are presented in Table 7.3 and show an increase in operational expenditures on intellectual property management but a fairly static income from those activities.

Table 7.3

Intellectual Property in Canada's Higher Education Sector

	2004	2005	2006	2007	2008
	$ Thousands				
Total operational expenditures for intellectual property management[a]	36,927	41,544	42,492	41,851	51,124
Income from intellectual property[a]	51,210	55,173	59,689	52,477	53,183
	Number				
Full-time equivalent employees engaged in intellectual property management	280	292	323	285	321
Invention disclosures[b]	1,432	1,452	1,356	1,357	1,613
Inventions protected[b]	629	761	707	668	820
Patent applications[c]	1,264	1,410	1,442	1,634	1,791
Patents issued[c]	397	376	339	479	346
Patents held[c]	3,827	3,961	4,784	4,185	5,908
New licences and options[d, e]	494	621	437	538	524
Active licences and options[d, e]	2,022	2,836	2,038	2,679	3,343

Notes:

a. Intellectual property refers to any creation of the human mind that can be protected by law.

b. An invention is any patentable product, process, machine, manufacture, or composition of matter, or any new and useful improvement of any of these.

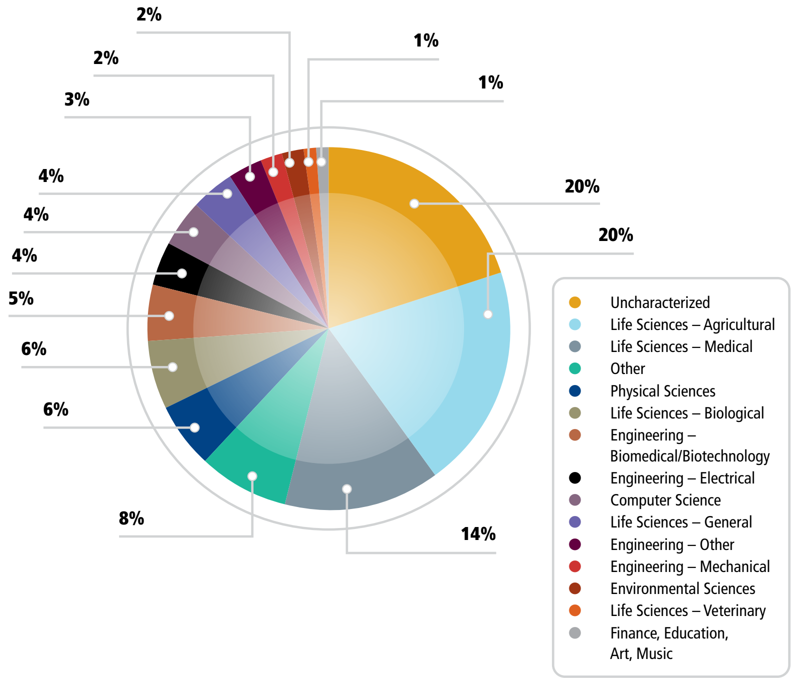
c. A patent is a document that protects the rights of an inventor. Patents are granted by the governments of countries.

d. A licence is an agreement with a client to use the institution's intellectual property for a fee or other consideration.

e. An option is the right to negotiate for a licence.

Data source: Statistics Canada (2010). *Survey of Intellectual Property Commercialization in the Higher Education Sector 2008*

The Association of University Technology Managers (AUTM) carries out an annual survey of key applied S&T outputs and IP indicators, invention disclosures, and patent applications at Canadian universities and research institutions. In a recent survey, AUTM analyzed invention disclosures by field of research (see Figure 7.7), showing that a large majority of disclosures are associated with the life sciences and engineering (AUTM, 2010).



Reproduced with permission from AUTM (2010). *AUTM Canadian Licensing Activity Survey: FY2009*

Figure 7.7

Invention Disclosures in 37 Canadian Universities by Field of Research, 2008

Another important metric relating to technology development and applied research in universities and colleges is the number (and types) of research partnerships and collaborations between Canadian academic institutions and businesses. Limited publicly available data are available on the breakdown of industry-university research contracts by sector or type of research. One such study performed by The Impact Group (2010) suggests that the majority of industry-sponsored contract research in Canada originates from just three sectors: pharmaceuticals and medicine, engineering and scientific services, and the environment (see Table 7.4). However, this study was based on a sample of only 20 institutions (eight medical/doctoral universities, three comprehensive universities, five undergraduate universities, and four research hospitals), and a more extensive investigation would be required to draw reliable conclusions.

Table 7.4
University-Industry Contracts by Contractor Type, 2010

Contractor Type	Number of Contracts	Percentage of Total
Pharmaceuticals & Medicine	158	27.7
Engineering & Scientific Services	84	14.7
Environment	70	12.3
Natural Resources	23	4.0
Power Generation	23	4.0
Chemicals & Materials	19	3.3
Software & Computer Services	19	3.3
Aerospace	16	2.8
Business, Management	14	2.5
Education	12	2.1
Scientific Services	11	1.9
Energy, Oil & Gas	10	1.8
Health	10	1.8
Electronic Parts & Components	9	1.6
Medical Devices & Instrumentation	9	1.6
Mining & Primary Metals	9	1.6
Social Sciences	9	1.6
Automotive	8	1.4
Transportation	8	1.4
Comm/Telecom Equipment	7	1.2
Computer Equipment	7	1.2
Tourism	6	1.1
Defense	4	0.7
Other	26	4.7
Total	**571**	**100.0**

Reproduced with permission from The Impact Group (2010).
Knowledge Transfer Through Research Contracting

Finally, Canada's colleges and polytechnics have been undertaking an increasing amount of applied S&T in recent years, often in cooperation with local businesses. Due to the growing importance of this activity to their overall role in the Canadian higher education landscape, colleges and polytechnics are now actively monitoring and recording many metrics related to applied S&T outputs. Box 7.2 highlights some of the output measures that are being tracked by these institutions.

Most of these other sources of data on applied R&D activity in Canada's higher education sector and public research organizations are not broken down by the field or type of research. As well, in many cases, data are available only for specific institutions, sectors, or regions, and are not available consistently across the country. As a result, while general statistics of this kind may illuminate certain facts about Canada's applied R&D strengths *in specific institutional settings*, their piecemeal nature precludes a systematic identification of Canada's research and technology strengths. The Panel thus concludes that there remains a need for more systematic and detailed data collection of metrics related to applied research and technology development activity in Canada.

Box 7.2
Applied S&T in Canada's Colleges and Polytechnics

A large and growing amount of applied S&T is now carried out in Canada's colleges and polytechnics. Community colleges offer technical and vocational training through certificates and predominantly diplomas; polytechnics are degree-granting and research-intensive institutions that also offer a full range of advanced applied education and professional credentials. Research in colleges and polytechnics is almost exclusively applied and oriented towards collaborating closely with Canadian businesses in research related to the development, demonstration, and commercialization of new technologies, products, and services. According to the Association of Canadian Community Colleges and Polytechnics Canada, in 2009–2010 colleges participated in 158 different research networks in Canada at local, regional, provincial, and national levels. The nine polytechnics in Canada worked with 1,085 industry partners, and across the college system a total of 4,051 companies participated in applied research projects with Canadian colleges and polytechnics in 2009–2010 (an increase of five per cent from the preceding year, and more than seven times the number recorded in 2005–2006). Additionally, colleges received $45 million in research funding from the private sector.

(ACCC, 2011)

7.5 CONCLUSIONS

The objective of this chapter was to evaluate Canada's research strengths as they relate to the development of new technologies, relying in particular on patents and related measures of knowledge application. While imperfect, patents remain one of the most robust and widely used indicators of applied S&T activity. According to the analysis of the data presented here, Canada performs poorly on many of these indicators relative to other leading S&T countries. Only three areas of patent activity in Canada emerge as clear strengths based on patent citations: AgriFood, Chemicals, and ICT. In general, Canada accounts for a relatively small proportion of world patents compared to its share of the world's scientific research. Canada also lags behind when it comes to royalties and licensing fees related to IP, and remains a net exporter of IP.

Canadian universities, colleges, and other publicly funded research organizations engage in a range of applied research and development activities, many of which are undertaken in close collaboration with Canadian businesses. The full extent of these activities is by no means captured by patents alone. The other data sources available, however, are typically not sufficiently granular to allow analysis of activities on a field-by-field basis. Additionally, they are not sufficiently detailed or inclusive to produce a cohesive picture of Canadian S&T related to technology development. These limitations point to an important gap in Canada's data collection activities related to applied research and technology development.

8

S&T Capacity

8 S&T Capacity

Key Findings

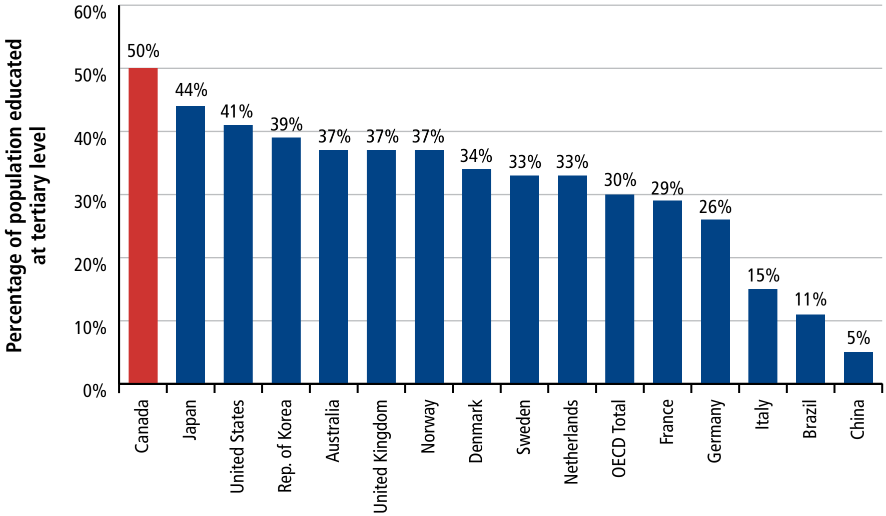
- From 2005 to 2009, there were increases in the number of students graduating from Canadian universities at the college, undergraduate, master's and doctoral levels, with the largest increase at the doctoral level.
- Canada ranks first in the world for its share of population with post-secondary education.
- International students comprise 11 per cent of doctoral students graduating from Canadian universities. The fields with the largest proportions of international students include Earth and Environmental Sciences; Mathematics and Statistics; Agriculture, Fisheries, and Forestry; and Physics and Astronomy.
- From 1997 to 2010, Canada experienced a positive migration flow of researchers, particularly in the fields of Clinical Medicine, Information and Communication Technologies (ICT), Engineering, and Chemistry. Based on Average Relative Citations, the quality of researchers emigrating and immigrating was comparable.
- In three-quarters of fields, the majority of top-cited researchers surveyed thought Canada has world-leading research infrastructure or programs.

S&T performance is critically dependent on S&T capacity, including access to highly qualified and skilled personnel and to infrastructure in the form of facilities, networks, and research programs. Although the charge to the Panel (see Chapter 1) did not explicitly ask for an assessment of S&T capacity, in the Panel's opinion it is fundamental to an assessment of the state of S&T in Canada. People and infrastructure are the "who" and the "where" of Canadian S&T. They do not in themselves denote strength, but Canadian research needs capacity in both of these areas to be strong now, and in order to build for the future.

8.1 STUDENTS GRADUATING IN CANADA

In general, Canada's population is well educated with 50 per cent of Canada's adult population between the ages of 25 and 64 having completed a post-secondary education (college or university). This places Canada first among comparator countries and ahead of both G7 and OECD averages (see Figure 8.1) and provides Canada with a solid basis of educated people to train in advanced degrees in S&T.

In addition to a high baseline, Canada has a growing population of individuals training in its post-secondary education system, from just over 319,000 in 2005 to approximately 370,000 in 2009, an increase of 15 per cent. In particular, between 2005 and 2009, individuals graduating with an undergraduate degree, a prerequisite for advanced research studies, grew by 14 per cent; and those with master's training grew by 17 per cent (see Table 8.1). Additionally, the number of graduates from the college sector increased by 17 per cent from 2005 to 2009.



Data source: OECD (2011b). *Education at a Glance 2011: OECD Indicators*

Figure 8.1

Percentage of Population (aged 25–64) Trained at the Post-Secondary Level, College and University

Data are for the year 2009. Tertiary education is defined as programs that are classified under the International Standard Classification of Education's levels 5A (theoretically based programs designed for entry into advanced research programs and highly skilled professions), 5B (technical/occupation specific programs) and 6 (advanced study and original research).

Table 8.1

Growth Rate of College and University Graduates by Program Level, 2005–2009

	Number of Students Graduating		
Academic level	**2009**	**2005**	**Growth rate, 2005–2009 (%)**
Undergraduate	170,106	149,766	13.6
College	155,442	132,600	17.2
Master's	38,304	32,730	17.0
Doctorate	5,673	4,194	35.3

Data source: Statistics Canada (2011d)

This table shows the number of graduates who have successfully completed an educational program during the reference year of the data collection. Data from the college sector represent career, technical or professional training programs and exclude post-career, technical or professional training programs or pre-university programs (e.g., general CÉGEP and associate degree programs).

The doctoral degree is recognized worldwide as evidence of high-level specialized research training. These professionals not only are capable of engaging in advanced academic scholarship, but also serve as instructors and mentors of the next generation of researchers, and provide leadership and capacity to Canada's industries and social and cultural organizations. From 2005 to 2009, the number of doctoral graduates from Canadian institutions grew substantially, with the largest percentage growth among comparable OECD countries (see Table 8.2). However, when compared to these same countries on a per capita basis, Canada ranked eighth in its production of doctoral graduates (see Figure 8.2).[28] This relatively low ranking in per capita doctoral graduates, compared with bibliometric measures (see Chapter 4), or reputation (see Chapter 5), is concerning because Canada's future performance in S&T depends on training or immigration of highly qualified and skilled people.

Table 8.2

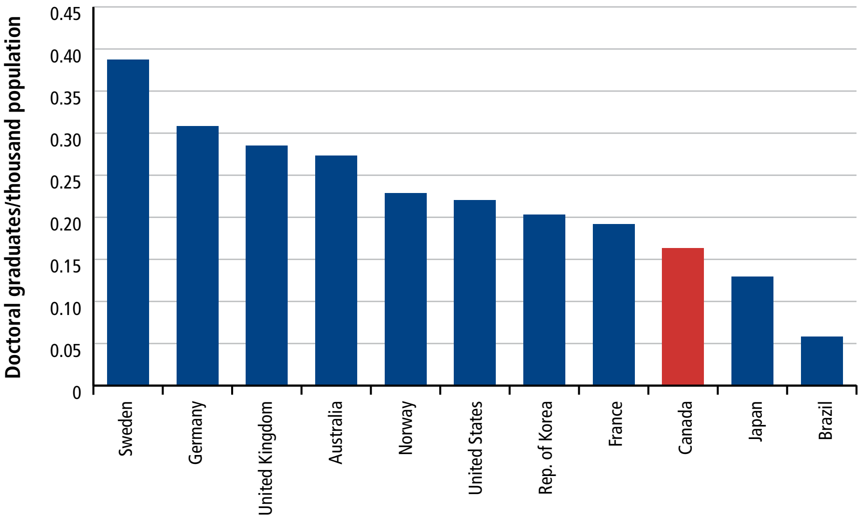
Number of Doctoral Graduating Students by Country

Country	2009	2005	Growth Rate (2005–2009) (%)
United States	67,716	52,631	28.7
Germany	25,527	25,952	-1.6
United Kingdom	17,651	15,778	11.9
Japan	16,476	15,286	7.8
France	11,941	9,578	24.7
Republic of Korea	9,912	8,449	17.3
Australia	5,808	4,886	18.9
Canada	5,440	4,116	32.2
Sweden	3,564	2,778	28.3
Netherlands	3,301	2,879	14.7
Norway	1,084	838	29.4

Data source: OECD (2011b). *Education at a Glance 2011: OCED Indicators*

Data are sorted according to number of doctoral students graduating in 2009. According to the International Standard Classification of Education (used by the OECD), doctoral programs are classified as level 6, advanced research programs. The data for Canadian doctoral graduates derived from the OECD database differ from the number in Table 8.1 derived from the Statistics Canada's socio-economic database (CANSIM). The CANSIM data use a variable called the Pan-Canadian Standard Classification of Education (PCSCE) – Aggregate 2 (Program Type), which provides an actual count of the number of graduates. The OECD uses Program Level, a variable that provides estimates of the number of graduates.

28 Comparable data on numbers of doctoral graduates in China and India were not available, but the number of doctoral graduates in these countries is recognized to be very large.



Data source: OCED (2011b). *Education at a Glance 2011: OECD Indicators*

Figure 8.2

Doctoral Students Graduating in 2009 per Thousand Population

For an explanation of the data utilized in this figure, see the table note in Table 8.2.

In contrast to the knowledge discovery role of doctoral degree-granting universities, colleges and polytechnics play an instrumental role in the S&T enterprise by equipping individuals with the technical and problem-solving skills required for applied research and technology development. Examination of the number of graduates from colleges per thousand population reveals that Canada ranks second among comparator countries, trailing behind Sweden but ahead of the larger industrialized nations of France, Germany, and the United States (OECD, 2009).

In terms of fields of study, Economics and Business, Social Sciences, and Public Health and Health Services produce the largest share of graduates from the college sector (see Table 8.3). At the undergraduate level these fields also account for the largest proportion of graduates, with the addition of Communication and Textual Studies, and Engineering. At the master's level, there were greater proportions of graduates in Economics and Business (presumably mainly MBAs), Social Sciences, Engineering, Public Health and Health Services, and Communication and Textual Studies. In contrast, at the doctoral level, Engineering had the greatest share of graduates followed by Social Sciences, Biomedical Research, and Psychology and Cognitive Sciences. Fields of bibliometric strength (see Chapter 4) with the highest rates of growth in doctoral graduates between 2005 and 2009 included ICT and Physics and Astronomy. Similarly, Astronomy and Astrophysics, a sub-field of strength identified in Chapter 4 (see Table 4.6), experienced the greatest growth in master's and doctoral degrees granted between 2005 and 2009, with a growth of 350 per cent in doctoral degrees and of 700 per cent in master's degrees. Nuclear and Particle Physics and Classics also had some of the strongest growth rates in master's degrees granted, both at 200 per cent. However, both Anatomy and Morphology and Zoology experienced some of the greatest declines in doctoral degrees granted in the same period (see Appendix 8).

Table 8.3

Distribution of Graduates by Field and Academic Level, 2009

Field	College	Undergraduate	Master's	Doctorate
Engineering	14,850	10,419	3,723	1,032
Social Sciences	22,179	40,869	8,874	705
Biomedical Research	135	4,437	1,077	579
Psychology & Cognitive Sciences	201	10,080	1,080	435
Economics & Business	37,764	35,037	9,831	315
Biology	366	7,038	792	294
Communication & Textual Studies	5,286	12,405	1,737	273
Clinical Medicine	7,437	4,680	576	264
Information & Communication Technologies	6,315	3,438	921	234
Chemistry	54	1,014	282	231
Physics & Astronomy	426	804	297	192
Earth & Environmental Sciences	1,086	1,926	963	177
Mathematics & Statistics	N/A	1,920	546	159
Agriculture, Fisheries & Forestry	1,560	933	408	153
Historical Studies	93	5,781	747	138
Public Health & Health Services	17,700	10,254	3,252	138
Philosophy & Theology	39	1,986	573	117
Visual & Performing Arts	6,042	7,092	915	93
Built Environment & Design	1,269	3,138	1,056	60
General Arts, Humanities & Social Sciences	3,864	5,529	207	48
Enabling & Strategic Technologies	600	159	111	3
General Science & Technology	543	1,140	21	3

Data source: Statistics Canada (2011d)

The data in this table are sorted by the number of doctorate degrees. The summation of graduates at each academic level may not correspond to the number of total graduates within that level. This is a result of Statistics Canada's practice of rounding student counts from the Postsecondary Student Information System to a multiple of three. The use of random rounding can create slight anomalies. Since sub-totals are also randomly rounded, they will not necessarily equal the sum of the randomly rounded component figures. This will likely be evident where frequencies are small. Fields listed in Statistics Canada's Classification of Instructional Programs (CIP) were reclassified to academic fields listed in the Science-Metrix ontology (see Appendix 8).

8.2 RESEARCHERS IN CANADA

According to the OECD's Frascati Manual (2002), researchers are "professionals engaged in the conception or creation of new knowledge, products, processes, methods and systems, as well as in the management of the projects concerned." On a per capita basis, Canada has a similar number of researchers to the United States and the United Kingdom, but fewer than Japan, Norway, and Sweden (see Table 8.4). Over the 2004–2008 period, there was modest growth in the number of researchers in Canada, although still considerably behind that of Brazil and China. Of the total researchers in Canada, 60 per cent work in the business sector, 6 per cent in government, and 33 per cent in higher education (see Figure 8.3).

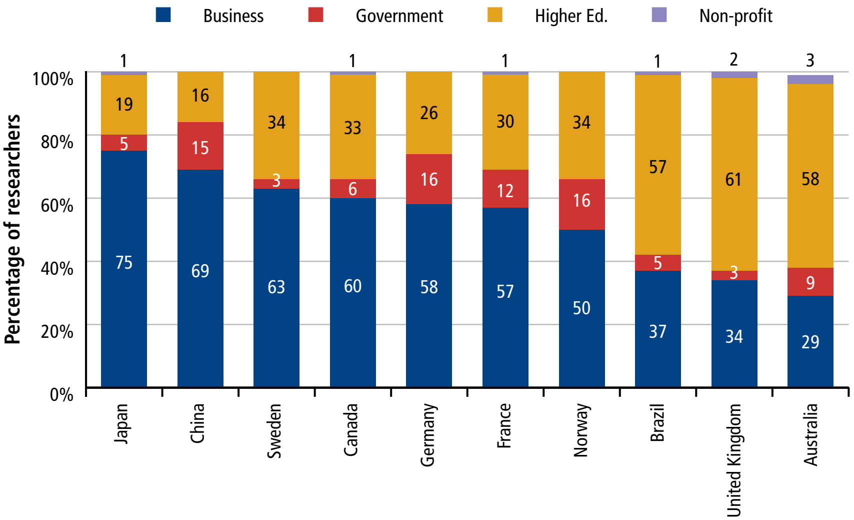
Table 8.4

Number of Researchers in Canada and Comparator Countries

Country	Researchers		Researchers/ million inhabitants (2008)	Growth rate (%)
	2004	2008		
Norway	21,163	26,605 [b]	5,504	25.70
Japan	653,747	656,676	5,190	0.40
Sweden	48,784	46,719 [b]	5,018	-4.20
United States	1,384,536	1,412,639 [a]	4,673	12.80
Canada	130,383	142,948 [a]	4,335	9.60
Australia	81,192	91,617	4,259	12.80
United Kingdom	228,969	235,373 [c]	3,794	2.80
Germany	270,215	311,500 [b]	3,780	15.30
France	202,377	229,130	3,689	13.20
China	926,252	1,592,420	1,199	71.90
Brazil	98,341	133,266	696	35.50

Data source: UNESCO Institute for Statistics (2011), Science & Technology Statistics (Database).

This table is sorted by researchers per million inhabitants. The data represent the number of researchers in 2008 except for a) Canada & U.S. (2007); b) Germany, Norway, Sweden (2009); c) United Kingdom (2010).



Data source: UNESCO Institute for Statistics (2011), Science & Technology Statistics (Database).

Figure 8.3

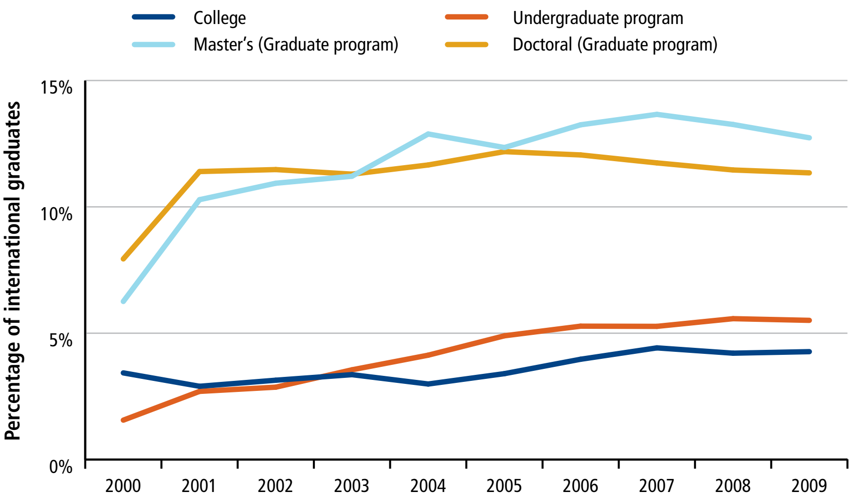
Researchers Engaged in R&D by Country and Sector of Performance, 2008

The OECD definition of "researcher" is used: professionals engaged in the conception or creation of new knowledge, products, processes, methods and systems, as well as in the management of these projects. The data represent the proportion of researchers in 2008 except for Canada (2007), Germany, Norway, Sweden (2009) and the United Kingdom (2010). Data were not available for the United States.

8.3 CIRCULATION OF HIGHLY QUALIFIED AND SKILLED PERSONNEL (HQ&SP)

8.3.1 International Students

The term "international students" refers to students who have intentionally entered Canada to undertake scholarship at a Canadian academic institution. From 2000 to 2009 there was a steady increase in the percentage of international graduates at all program levels in Canada (see Figure 8.4), accounting for six per cent of graduates in 2009. In particular, international students comprised 12 per cent of all graduates at the master's level and 11 per cent at the doctoral level, demonstrating the attractiveness of advanced research programs in Canada. The fields with the largest proportions of international doctoral graduates included Enabling and Strategic Technologies; Earth and Environmental Sciences; Mathematics and Statistics; Agriculture, Fisheries, and Forestry; and Physics and Astronomy (see Table 8.5). With the exception of Agriculture, Fisheries, and Forestry, these fields were not among the Canadian fields ranked the highest in the survey of top-cited international researchers (see Chapter 5). There are several possible explanations for this apparent discrepancy. International students may select Canada because of its international reputation for overall S&T strength rather than for any field-specific strength, or they may be attracted to specific researchers or institutes whose excellence in a field is not reflected in aggregated national statistics. Students may also select Canada for specific fields of study that are not available in their home country or region, or they make choices based on financial, social, or personal considerations.



Data source: Statistics Canada (2011d)

Figure 8.4

Percentages of International Graduates by Program Level

International graduates are defined as individuals who at the time of the granting of their degree were students on a valid student visa in Canada.

Table 8.5

Percentage of International Doctoral Graduates by Field, 2005–2009

Field	Percentage (%)
Enabling & Strategic Technologies	50.0*
Earth & Environmental Sciences	25.7
Mathematics & Statistics	25.3
Agriculture, Fisheries & Forestry	23.0
Physics & Astronomy	19.5
Engineering	17.5
Information & Communication Technologies	15.7
Biology	15.1

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Field	Percentage (%)
Chemistry	15.0
Philosophy & Theology	14.9
Visual & Performing Arts	14.2
Built Environment & Design	13.9
Economics & Business	13.6
Historical Studies	13.3
Communication & Textual Studies	11.5
Social Sciences	9.8
Clinical Medicine	9.5
Biomedical Research	8.1
General Arts, Humanities & Social Sciences	7.7
Psychology & Cognitive Sciences	4.9
Public Health & Health Services	4.0
General Science & Technology	0

Data source: Statistics Canada (2011d)

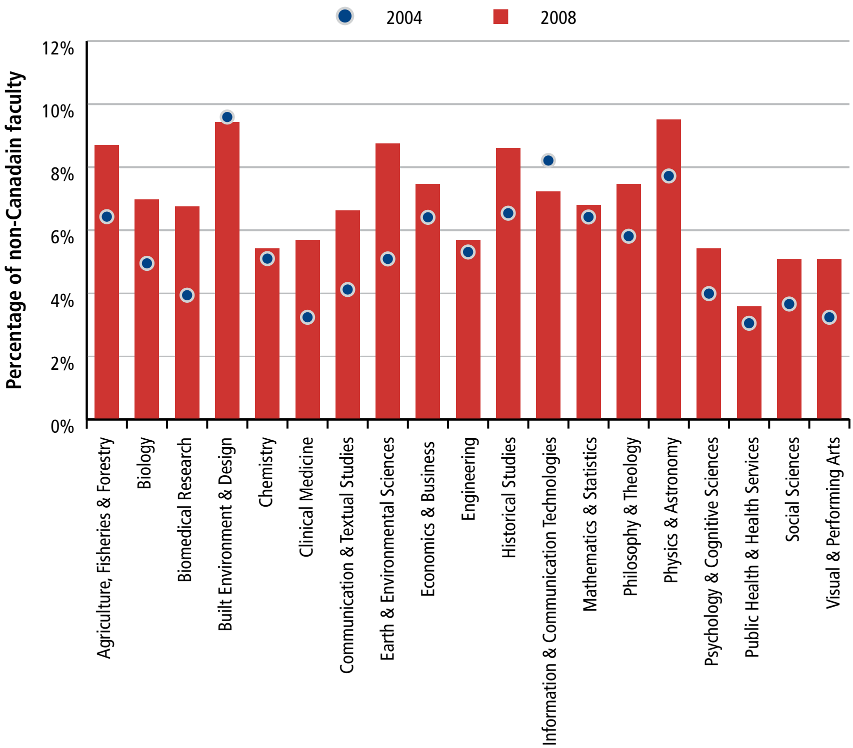
The counting of graduates at each academic level may not correspond to the number of total graduates within that level. This is a result of Statistics Canada's practice of rounding student counts from the Postsecondary Student Information System to a multiple of three. The use of random rounding can create slight anomalies. Since sub-totals are also randomly rounded, they will not necessarily equal the sum of the randomly rounded component figures. This will likely be evident where frequencies are small.

*The total designated to this field was 12, of whom six were international students.

Fields listed in Statistics Canada's Classification of Instructional Programs (CIP) were reclassified to academic fields listed in the Science-Metrix ontology (see Appendix 8).

8.3.2 International Researchers

Attracting international researchers to Canada is one way to enhance the output and impact of Canadian S&T. In 2008 the number of faculty on work visas at Canadian colleges and universities was 5,238. This accounted for 6 per cent of total faculty members, an increase of 21 per cent compared to 2004. The fields with the largest proportion of faculty members working on visas included Physics and Astronomy; Built Environment and Design; Agriculture, Fisheries, and Forestry; and Earth and Environmental Sciences (see Figure 8.5). There is no clear correlation between the number of international researchers and Canada's international reputation (see Chapter 5) or bibliometric impact or output (see Chapter 4). This indicates that for international researchers the attractiveness of Canada is likely due to factors other than national strengths. It is probable that researchers will be more concerned with the research program at the institution they are working in, as well as personal, economic, and social considerations.



Data source: Statistics Canada (2011b). *Science Statistics*

Figure 8.5

Percentage of Non-Canadian Faculty by Field

Faculty is defined as full-time teaching staff at Canadian degree-granting institutions. Subject fields taught and listed in Statistics Canada's Classification of Instructional Programs (CIP) were reclassified to academic fields listed in the Science-Metrix ontology (see Appendix 8).

8.3.3 Researcher Migration

Researcher migration refers to a temporary or permanent change in country of affiliation. New techniques in bibliometric analysis can identify these trends by examining changes in institutional affiliations of publishing researchers. Such information facilitates the calculation of rates of immigration, emigration, and transitory migration (temporary emigration of Canadian citizens from Canada and temporary immigration of foreign nationals to Canada). To gain some perspective on researcher migration, Science-Metrix used a sample of 22,579 researchers who possessed unique author identification markers (AUID) in Scopus (indicating that all papers assigned to that author are correctly assigned).[29] These were researchers who had published in at least three different years between 1997 and 2010, and who had published at least 10 papers; in other words they are all established researchers (see Appendix 1 for a detailed description of the methodology).

During the period 1997–2010, Canada experienced a positive migration flow (0.9 per cent) with more immigrants (about 900) than emigrants (about 700). Immigrants and emigrants had comparable Average Relative Citations (ARC) scores, of 1.53 and 1.57 respectively, high scores for both groups. Over the same period, Canada was able to attract seven times as many temporary foreign workers than Canadian researchers who temporarily emigrated before returning. The ARC scores of foreign researchers who came to Canada temporarily were higher than those of Canadians who went abroad and then returned (see Table 8.6). Overall, Canada is maintaining its share in a highly competitive, global environment.

Table 8.6

Researcher Migration Trends in Canada, 1997–2010

Migration pattern	Number of researchers	Percentage of sample (%)	Average Relative Citations (ARC)
Emigration	711	3.1	1.57
Immigration	903	4.0	1.53
Temporary migration of Canadians	106	0.5	1.36
Temporary migration of foreign nationals	766	3.4	1.52
Net migration into Canada	192	0.9	–
Sample	22,579	100.0	1.34

Data source: Calculated by Science-Metrix using Scopus database (Elsevier)

"Temporary migration of Canadians" defines individuals who temporarily relocated to conduct research in another jurisdiction before returning to Canada. "Temporary migration of foreign nationals" defines individuals who temporarily resided in Canada to conduct research before relocating to their home or another jurisdiction.

29 Because the name of an author often appears under many different forms in Scopus (e.g., Rogers D, Rogers D.M, and Rogers Daniel M. all denote Daniel Michael Rogers) and because a name can match many authors (e.g., Rogers D. can refer to Daniel Michael Rogers as well as David Rogers), the names of authors as they appear in the database cannot be used to investigate migration unless the names are thoroughly cleaned to match an author to only those papers he or she published. Cleaning author names, however, is time consuming and expensive.

Analysis of migration trends at the field level revealed that ICT had the highest net migration into Canada with a net inflow of 56 researchers (see Table 8.7), followed by Clinical Medicine (with 45) and Engineering (with 29). The fields that attracted the greatest number of temporary foreign researchers included Clinical Medicine, Physics and Astronomy, Biomedical Research, ICT, and Chemistry.

Table 8.7

Researcher Migration Trends in Canada at the Field Level, 1997–2010

Field	Emigration		Immigration		Temporary emigration from Canada		Temporary immigration to Canada		Net migration into Canada	
	#	%	#	%	#	%	#	%	#	%
ICT	53	3.0	109	6.1	14	0.8	49	2.7	56	3.1
Engineering	25	1.7	54	3.7	1	0.1	37	2.6	29	2.0
Chemistry	51	4.3	61	5.1	7	0.6	46	3.8	10	0.8
Clinical Medicine	213	3.7	258	4.5	40	0.7	255	4.4	45	0.8
Physics & Astronomy	98	5.5	104	5.8	18	1.0	69	3.8	6	0.3
Biomedical Research	57	2.6	61	2.8	6	0.3	65	3.0	4	0.2
Enabling & Strategic Technologies	37	3.3	39	3.5	4	0.4	39	3.5	2	0.2

Data source: Calculated by Science-Metrix using Scopus database (Elsevier)

Data are presented for fields with at least 1,000 AUIDs in the sample. "%" is the percentage of the total sample. "Temporary emigration from Canada" refers to individuals who temporarily relocated to conduct research in another jurisdiction before returning permanently to Canada. "Temporary immigration to Canada" refers to individuals who temporarily resided in Canada to conduct research before relocating to their home or an alternative jurisdiction. The data are sorted according to the net migration of researchers into Canada.

8.4 INFRASTRUCTURE

In addition to highly qualified and skilled personnel, the capacity to perform world-leading S&T requires research support, programs, and infrastructure. This aspect of research capacity was assessed through the surveys of Canadian S&T experts and international researchers.

8.4.1 Survey of Top-Cited International Researchers

The world's top-cited researchers were asked if they felt that Canada had world-leading research programs or infrastructure in their field. Over half of the 5,154 respondents thought that Canada had world-leading capacity in their field, with the highest percentages in the Visual and Performing Arts (75 per cent, see Spotlight on the Arts and Digital Media later in this chapter), Mathematics and

Statistics (66 per cent), and Physics and Astronomy (66 per cent) (see Table 8.8).[30] The high proportion of respondents who indicated that they "don't know" was expected based on the survey sample (top-cited researchers in the world, whether or not they had knowledge of Canada). Even though less than 10 per cent of the respondents had ever worked or studied in Canada (see Chapter 5), in over three-quarters of the fields, the majority identified Canada as having world-leading infrastructure or research programs, indicating that the international reputation of Canadian research is high.

Table 8.8

Responses to the Question, "Does Canada have world-leading research programs or infrastructure of worldwide importance?" in the Survey of Top-Cited International Researchers

Field	Yes (%)	No (%)	Don't know (%)	Total Responses
Visual & Performing Arts	75	8	17	12
Mathematics & Statistics	66	4	31	198
Physics & Astronomy	66	5	29	406
Public Health & Health Services	65	9	27	175
Agriculture, Fisheries & Forestry	63	6	31	173
Psychology & Cognitive Sciences	63	6	31	182
Earth & Environmental Sciences	61	7	33	428
Biomedical Research	59	9	32	663
Clinical Medicine	59	7	34	419
Biology	55	7	38	293
Historical Studies	53	10	36	58
Enabling & Strategic Technologies	52	8	40	212
Engineering	52	7	41	749
Chemistry	52	9	39	433
Economics & Business	51	15	34	92
Social Sciences	51	11	39	152
Philosophy & Theology	49	8	43	49
Information & Communication Technologies	44	10	47	357
Built Environment & Design	43	10	47	51
Communication & Textual Studies	35	2	63	51
Total	**56**	**8**	**36**	**5,154**

30 The full text of these responses is available in the survey database on request from the Council of Canadian Academies.

8.4.2 Survey of Canadian S&T Experts

Table 8.9 presents the opinion of Canadian S&T experts on Canada's research infrastructure. The Canada Research Chairs program, Canada's universities and research hospitals, the Canada Foundation for Innovation (CFI), and the Canadian Institutes of Health Research (CIHR) were identified as S&T advantages for Canada by over 85 per cent of respondents. The results of this question cannot be directly compared with the same question in 2006 due to differences in sampling methodologies (see Chapter 2). Nevertheless, the results indicate, in general, that there is a high degree of concordance between these results and those of the 2006 survey.

To some degree, these results follow the research investment trends described in Chapter 3, wherein Canada had relatively high levels of investment in S&T performed in higher education (HERD), and relatively lower levels in S&T in the business sector (BERD). Similarly, infrastructure usually associated with supporting S&T in the higher education sector, such as the granting councils, universities, and research hospitals, is most often thought of as an advantage for Canada, whereas infrastructure usually associated with supporting S&T in the business sector, such as venture capital providers, tends to be among those least often described as being an advantage to Canada.

Table 8.9

Opinions of Canadian S&T Experts on Canada's Research Infrastructure

	2011			2006		
	Advantage (%)	Neither (%)	Disadvantage (%)	Advantage (%)	Neither (%)	Disadvantage (%)
Canada Research Chairs	88	7	5	82	12	6
Canada's Universities	87	8	4	80	13	7
Canada Foundation for Innovation (CFI)	87	7	6	82	12	6
Canada's Research Hospitals	86	8	6	80	13	7
Canadian Institutes of Health Research (CIHR)	85	8	7	78	13	8
Canadian Light Source Synchotron	83	14	3	73	21	5
Natural Sciences and Engineering Research Council (NSERC)	81	11	9	78	13	9
Sudbury Neutrino Observatory (SNO)	80	17	3	74	20	6
Genome Sequencing Centres	77	17	6	–	–	–
Canadian Research Icebreaker (Amundsen)	77	21	2	69	25	6
Networks of Centres of Excellence	77	12	11	73	16	12

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	2011			2006		
	Advantage (%)	Neither (%)	Disadvantage (%)	Advantage (%)	Neither (%)	Disadvantage (%)
TRIUMF (UBC)	73	21	6	64	27	9
High Performing Computing Networks	73	18	9	64	28	9
Social Sciences and Humanities Research Council (SSHRC)	72	18	11	62	25	13
Canada Excellence Research Chairs (CERCs)	71	17	11	–	–	–
Statistics Canada	71	18	11	–	–	–
Perimeter Institute	71	23	6	–	–	–
National Research Council Institutes	68	18	13	72*	16*	11*
Genome Canada and Regional Centres	67	20	13	68	18	14
Provincial/Territorial Research Funding Programs	66	19	15	54	19	27
Infectious Diseases Laboratories	65	27	7	78	17	5
NRC's Industrial Research Assistance Program (IRAP)	64	21	15	76	16	8
Provincial Research Councils	64	18	18	47	27	26
SR&ED Tax Credit	63	22	15	73	19	8
CANARIE High-Speed Network	63	27	9	65	28	7
NRU Reactor (AECL)	62	28	10	55	35	10
SSHRC Research Data Centres	58	30	12	56	33	11
Astronomical Observatories	58	32	10	57	34	9
Canada Council for the Arts	57	33	11	–	–	–
Federal Laboratories and Facilities	56	26	18	72*	16*	11*
University Technology Transfer	56	23	21	48	28	24
NEPTUNE Canada	56	39	5	–	–	–
Canadian Institute for Advanced Research (CIFAR)	55	34	11	56	32	13
International Development Research Centre (IDRC)	55	30	15	48	32	20
Centres of Excellence for Commercialization and Research (CECR)	53	26	21	–	–	–
Library and Archives Canada (LAC)	53	36	11	52	36	12
Intellectual Property Protection	51	36	12	43	39	18
Federal Support Programs for Technology-intensive Business	51	27	22	56	27	17
Canada's Polytechnics	50	40	10	–	–	–
Health and Safety Regulation	50	38	11	45	38	17

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	2011			2006		
	Advantage (%)	Neither (%)	Disadvantage (%)	Advantage (%)	Neither (%)	Disadvantage (%)
Provincial Government Support Programs for Technology-intensive Business	49	27	24	51	24	25
Charitable Support for Research	48	22	30	36	26	38
VENUS Canada	48	46	6	–	–	–
Canadian Research Knowledge Network (CRKN)	47	40	13	41	46	13
Sustainable Development Technology Canada	47	36	16	47	37	15
Council of Canadian Academies (CCA)	46	41	13	–	–	–
Environmental Regulation	46	36	18	40	39	21
Provincial Laboratories and Facilities	46	27	28	–	–	–
Business-led NCEs	44	34	22	–	–	–
Canada's Banking System	37	30	33	16	36	48
Copyright Regulation	37	43	20	–	–	–
Business Framework Regulations	37	47	16	32	46	23
Export Development Canada (EDC)	36	41	24	39	41	20
College/Polytechnic Technology transfer	36	38	25	–	–	–
Canada's Community Colleges	34	44	22	40	44	16
Business Development Bank of Canada (BDC)	32	38	30	31	39	29
S&T Counselors (Foreign Affairs and International Trade Canada)	29	40	31	39	41	20
Venture Capital Providers	27	27	46	29	25	46
Canadian Commercial Corporation (CCC)	23	46	31	25	53	21

This table presents the answers in 2006 and 2011 to the following question: "For the following elements where you are comfortable expressing a view, please rate your opinion of the degree of advantage they provide for Canadian research and/or technological application relative to other advanced countries (i.e., roughly the OECD group)." Those items labeled with a dash (–) were not part of the 2006 survey. The table is ranked by "Advantage" in the 2011 survey. Survey respondents were asked to rate each infrastructure on a 7-point scale. A rating from 5–7 is reported as an "Advantage, " a rating of 4 is reported as "Neither," and a rating of 1–3 is reported as a "Disadvantage." A small number of organization titles were corrected. These titles are therefore slightly different than those that appeared in the survey.

* In 2006, NRC institutes and federal laboratories were together in one question. These were separated for 2011 survey.

8.5 COMPARISON WITH THE 2006 REPORT

The analysis of highly qualified and skilled personnel in Canada is a new element in this assessment and therefore cannot be compared with the 2006 report. The survey of Canadian S&T experts regarding Canada's S&T infrastructure and support programs produced results very similar to those of 2006.

Spotlight on the Arts and Digital Media

Cultural expression is deeply rooted as part of Canada's intellectual traditions and has become a significant component of its economic capacity, contributing over four per cent of Canada's gross domestic product (Conference Board of Canada, 2008). Canada is home to comprehensive universities with well-established fine and performing arts programs and a network of independent art and design institutions located in Vancouver, Calgary, Banff, Toronto, and Halifax. These institutions spawn and strengthen creative centres — cities and regions with a strong cultural life and institutions such as museums, galleries, theatres, and orchestras that act as magnets for talent and investment. As well as nationwide research capacity there are three significant Canadian hubs in the Vancouver area, the greater Toronto area, and Montréal. The growth of research capacity and practice has been recognized in Canada by the Social Sciences and Humanities Research Council of Canada. The Fonds de recherche du Québec — Société et culture (FQRSC) has played a significant role in building fine and performing arts research excellence in Quebec, Canada's leader in research performance in this field.

Strong arts and ICT sectors, and Canada's recent focus on a digital economy strategy, have resulted in significant investments in research in digital media as well as underlying technologies. Digital media research centres bring visual and performing arts together with interdisciplinary research and industry, and cross several fields including Communications and Textual Studies, ICT, and Visual and Performing Arts. For example, the Graphics, Animation and New Media (GRAND) Network of Centres of Excellence (NCE) involves collaborations among visual and performing arts, design, and scientific and social science research in the digital media context. The Digital Media Research and Innovation Institute at OCAD University in Toronto encompasses inclusive design, data visualization, and mobile and digital media, funded by the Ontario and federal governments, industrial partners, and the Canada Foundation for Innovation (CFI) through its support of the Inclusive Design Institute. Hexagram in Montréal, created with funding from the CFI and the Government of Quebec, is the largest Canadian consortium for research in new media art, design, and interactive performance and technologies, bringing together more than 80 researchers from Concordia University and l'Université du Québec à Montréal as well as more recently the Université de Montréal and McGill University. Emily Carr University of Art + Design built its Intersections Digital Studios with support from the CFI and the Government of British Columbia.

Collectively, these institutes have attracted talent, undertaken and circulated research in Canada and well beyond, and have served as models for researchers and institutions in other countries.

8.6 CONCLUSIONS

Capacity, in the form of highly qualified and skilled personnel and infrastructure, is crucial to current and future S&T strength. The evidence relating to Canada's performance in this area is mixed.

Canada has the largest number of post-secondary graduates in the OECD — a strong basis to build from — but is not translating this into high numbers of doctoral graduates who will conduct S&T in the future. The same trend was observed by the Science, Technology and Innovation Council (2011) along with comparatively high unemployment rates for doctorate holders, a potential disincentive to commit to doctoral study. Immigration of researchers is another way to increase S&T capacity and Canada seems to be attracting roughly as many researchers, of about the same strength in terms of research impact, as it is losing (though these data do not include recent initiatives such as the Canada Excellence Research Chairs).

World-class infrastructure is essential, both for conducting S&T and for attracting the best collaborators. The evidence collected by the Panel shows Canada performing well here, in the opinions of top-cited international researchers. Several infrastructure programs are perceived by Canadian S&T experts as a distinct advantage to Canadian S&T including the Canada Research Chairs program, Canada's universities and research hospitals, the Canada Foundation for Innovation, and the Tri-Council research funding agencies.

In general, Canada has good capacity in S&T. Canada's infrastructure and programs supporting discovery-based research are particular strengths. However, Canada is behind some other countries in terms of number of researchers, and the training of the next generation of researchers.

9

Regional S&T Strengths

9 Regional S&T Strengths

Key Findings

- Bibliometric analysis indicates that, among the provinces and territories, Ontario and Quebec produce the largest number of research papers, and British Columbia leads in terms of citation-based measures of impact.
- Canadian researchers identified Ontario, Quebec, Alberta, and British Columbia as Canada's strongest provinces for research.
- Ontario is the main hub of Canada's collaboration network, but smaller provinces and the territories have the highest collaboration rates.
- Ontario is the leading province for total intellectual property ownership, but Quebec is the only province with a positive flow of intellectual property.
- Quebec, Ontario, Alberta, and British Columbia had the largest proportion of doctoral students per thousand population graduating in 2009.

The Panel was charged with assessing how S&T strengths are distributed geographically across the country, and chose the province or territory as the most meaningful geographical region in Canada, even though comparisons are difficult across jurisdictions of such vastly diverse sizes (see Table 9.1) and economies.

Table 9.1

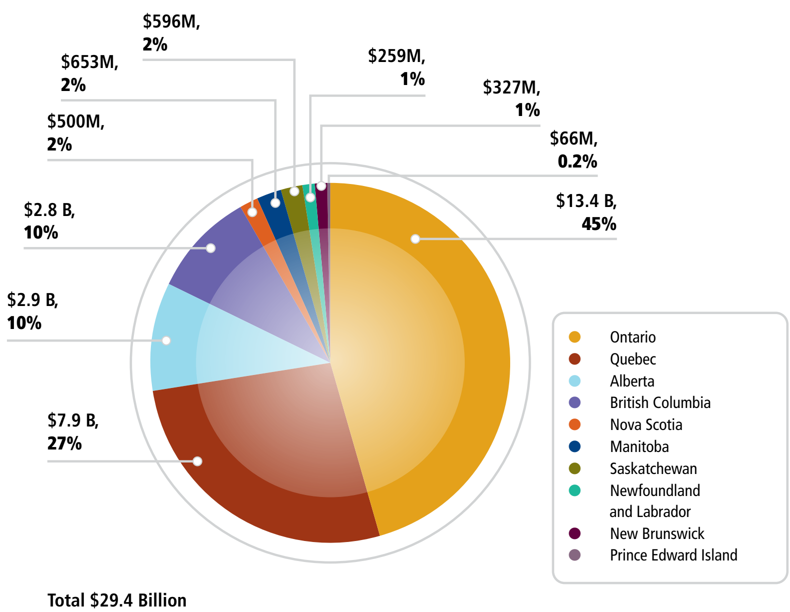
The Population of Canadian Provinces and Territories (2011 Census)

Province or Territory	Population	Percentage of Total Population (%)
Ontario	12,851,821	38.4
Quebec	7,903,001	23.6
British Columbia	4,400,057	13.1
Alberta	3,645,257	10.9
Manitoba	1,208,268	3.6
Saskatchewan	1,033,381	3.1
Nova Scotia	921,727	2.8
New Brunswick	751,171	2.2
Newfoundland and Labrador	514,536	1.5
Prince Edward Island	140,204	0.4
Northwest Territories	41,462	0.1
Yukon	33,897	0.1
Nunavut	31,906	0.1
Canada	33,476,688	100.0

Data source: Statistics Canada (2012c). *Population and dwelling counts, for Canada, provinces and territories, 2011 and 2006 Censuses*

9.1 R&D INPUTS BY PROVINCE

As discussed in Chapter 3, R&D investment, although not a direct measure of research strength, provides valuable context. Figure 9.1 shows the breakdown by province of Canada's overall R&D spending in 2009. This includes spending from federal, provincial, industrial, and other sources. The four provinces with the largest populations (Ontario, Quebec, British Columbia, and Alberta — see Table 9.1) also have the highest R&D spending. Ontario alone accounted for nearly one-half of all spending in Canada, and Ontario and Quebec together accounted for close to three-quarters of all spending. Alberta and British Columbia accounted for about 10 per cent each, and the other provinces combined for 8 per cent. The share of the territories is less than 1 per cent, and is not shown.

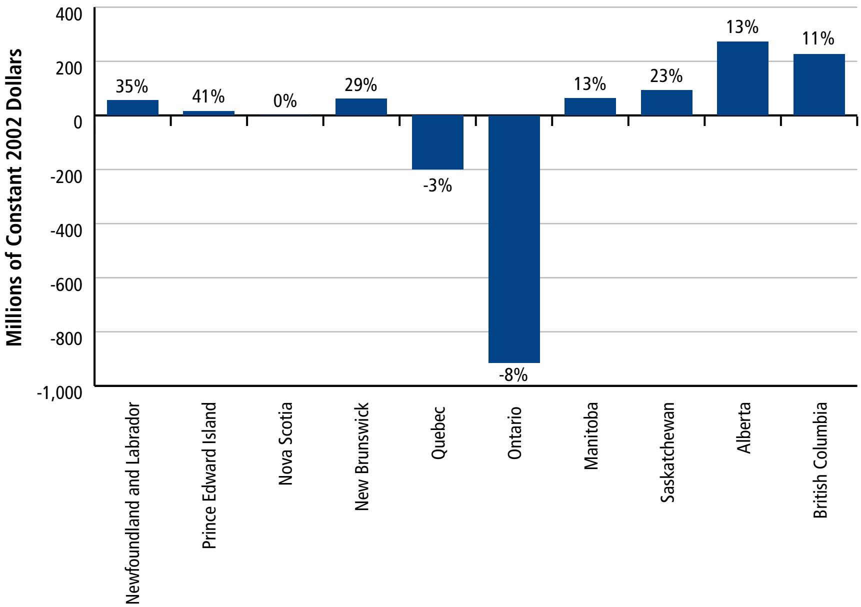


Data source: Statistics Canada (2012a). *Gross Domestic Expenditure on Research and Development in Canada (GERD), and the Provinces*

Figure 9.1

Provincial Distribution of Gross Domestic Expenditures (current dollars) on Research and Development, 2009

Chapter 3 reported a decline in Canadian R&D spending over the past six years, but this decline was not evenly distributed across the country. Spending declined in Ontario and Quebec, and increased in Newfoundland and Labrador, Prince Edward Island, New Brunswick, Alberta, British Columbia, and Saskatchewan (see Figure 9.2).



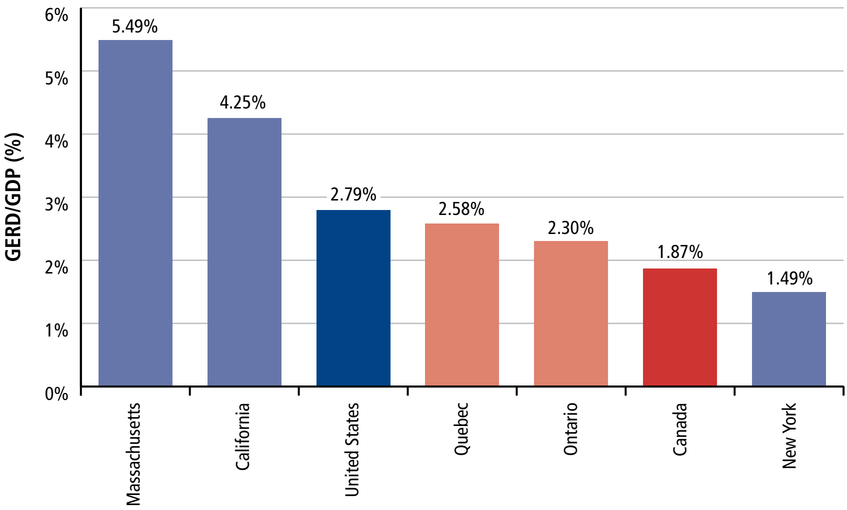
Note: The percentage change for the period is shown above/below the change line in absolute dollars.
Data source: Statistics Canada, CANSIM Table 358-0001

Figure 9.2

Change in Provincial Gross Domestic Expenditure on Research and Development, 2004–2009 (constant 2002 dollars)

The bars in this figure show the change in expenditures in the period 2004–2009 in constant 2002 dollars. However, due to the vastly different 2004 levels of spending, these changes represent different percentage increases/decreases—for example,Ontario experienced almost a $1 billion decrease, representing an 8 per cent decrease. In contrast, an addition of $100 million in Saskatchewan represented a 23 per cent increase. Percentage changes are shown above and below the change line in this figure.

Despite these shifts, Ontario and Quebec maintain the highest provincial ratios of gross domestic expenditure on R&D (GERD) to GDP (see Table 9.2), with ratios that are above the OECD average. However, when compared with other sub-national jurisdictions such as American states renowned for their S&T (e.g., Massachusetts and California), the GERD to GDP ratio of Ontario and Quebec appears much more modest (see Figure 9.3). It is likely that the high levels of business spending on S&T in these states (for example Silicon Valley in California) accounts for much of this difference.



Note: The 2008 data are the latest data available for the U.S. so 2008 Canadian data are used for comparative purposes.
Data source: Statistics Canada (2012a). *Gross Domestic Expenditure on Research and Development in Canada (GERD), and the Provinces*; National Science Board (2012). *Science and Engineering Indicators, 2012*

Figure 9.3

Gross Domestic Expenditure on R&D (GERD) as a Percentage of GDP in Selected Jurisdictions, 2008

Business expenditure accounts for approximately half of all expenditures on research and development in Quebec, British Columbia, Ontario, and Alberta, as demonstrated by their relatively high BERD/GERD ratios compared with the other six provinces, which have BERD/GERD ratios well below 50 per cent. As described in Chapter 3, a ratio of below 50 per cent is often associated with small and developing economies (see Table 9.2).

Table 9.2

Provincial Distribution of Expenditures on Research and Development by Performing Sector, 2009

	Canada	ON	QC	AB	BC	MB	SK	NS	NB	NL	PEI
	Millions of Dollars										
All sectors (GERD)	29,430	13,386	7,855	2,851	2,798	653	596	500	327	259	66
Fed. Gov.	2,762	1,811	396	108	115	112	72	67	37	25	15
Prov. Gov.	420	51	99	138	25	8	84	0	13	0	0
BERD	15,110	6,971	4,581	1,420	1,502	204	129	89	119	81	9
HERD	11,013	4,555	2,779	1,185	1,157	328	311	345	158	153	41
GDP	1,528,985	581,635	304,861	240,697	191,863	51,518	57,995	34,774	27,920	24,762	4,778
GERD/GDP %	1.92	2.30	2.58	1.18	1.46	1.27	1.03	1.44	1.17	1.05	1.38
BERD/GERD Ratio	0.51	0.52	0.58	0.50	0.54	0.31	0.22	0.18	0.36	0.31	0.14

Note: This table is sorted by gross domestic expenditure on research and development (GERD).
Data source: Statistics Canada (2012a). *Gross Domestic Expenditures on Research and Development in Canada (GERD), and the Provinces*

9.2 RESEARCH OUTPUT AND IMPACT BY PROVINCE

Canada's four most populous provinces have the highest output and impact of research, both in absolute terms and when normalized by number of researchers. Ontario produced the largest number of research papers (over 180,000) during the 2005–2010 period (see Table 9.3), followed by Quebec (over 88,000 papers), British Columbia (60,000), and Alberta (51,000). On a per capita basis, British Columbia and Alberta were the top provinces in terms of papers published per faculty researcher, followed by Ontario and Quebec. British Columbia had the highest ARC score.

Table 9.3

Number of Faculty Researchers, Published Papers and Average Relative Citations (ARC) Scores by Canadian Provinces and Territories, 2005–2010

Province or Territory	Average Relative Citations	Number of Faculty Researchers (2008)	Number of papers	Publications per faculty researcher
British Columbia	1.50	4,566	60,105	13.2
Ontario	1.37	15,960	182,180	11.4
Quebec	1.28	9,450	88,651	9.4
Alberta	1.24	4,194	51,752	12.3
Manitoba	1.23	1,698	13,367	7.9
Nova Scotia	1.17	2,151	15,361	7.1
Newfoundland and Labrador	1.15	912	5,324	5.8
Saskatchewan	1.13	1,599	13,969	8.7
Northwest Territories	1.12	N/A	220	N/A
New Brunswick	1.02	1,197	6,492	5.4
Prince Edward Island	1.00	225	1,129	5.0
Nunavut	N/A	N/A	112	N/A
Yukon	N/A	N/A	154	N/A
Canada	1.36	–	**395,369**	9.4
World	1	–	9,586,347	–

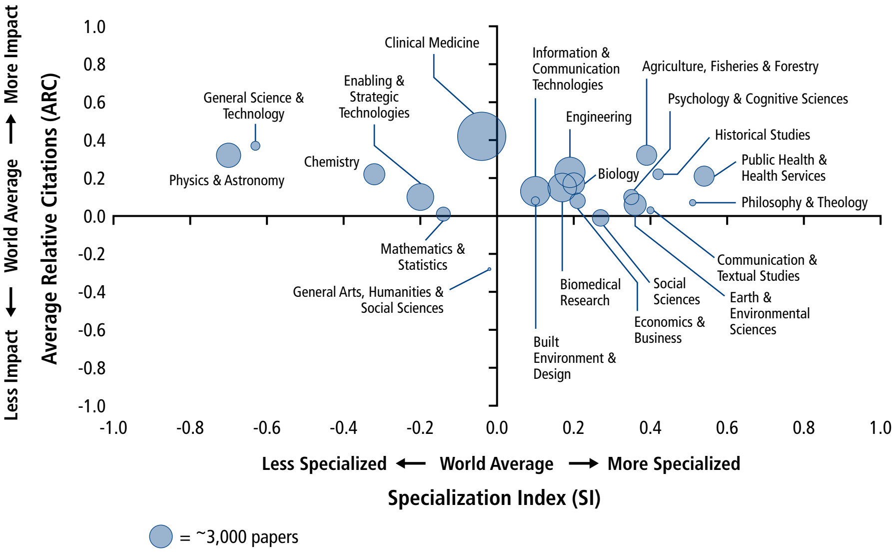
Note: The number of papers does not add to the Canadian total due to whole counting of papers (papers with authors in multiple provinces are counted more than once).
Data source: Calculated by Science-Metrix using Scopus database (Elsevier); Faculty data from Statistics Canada (2011c)

In addition to differences in research output, provinces also differ in their fields of strength. A summary of provincial strengths is presented in the positional analyses in Figure 9.4. As with the national positional analyses provided in Chapter 4, these figures are divided into four quadrants. The top-right quadrant contains fields with both relatively high research impact (frequency of citations compared to the world average) and a high level of research output (number of papers compared to expected, based on world averages). The top-left contains fields with a high level of impact in the field, but a relatively low level of output. The bottom-left indicates both low levels of impact and output; and the bottom-right indicates fields with relatively high levels of output, but relatively low levels of impact.

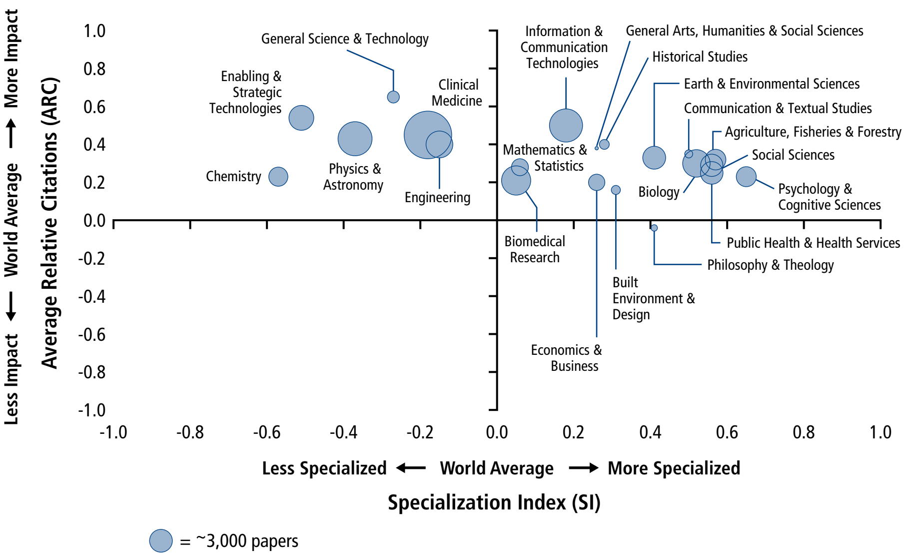
As noted in Chapter 4 (see Figure 4.6), nearly all fields of research in Canada are located in the upper-right and upper-left quadrants. It is therefore not surprising that the same applies for the four provinces (Ontario, Quebec, British Columbia, Alberta) that together account for 97 per cent of Canada's research output. These two quadrants indicate a research impact (ARC) that is above the world average. Similarly, for several of the large fields of research (for example, Physics and Astronomy; Clinical Medicine; Engineering; and Agriculture, Fisheries, and Forestry), the distribution of the fields between the upper right and upper left quadrants is relatively consistent across the four provinces, again reflecting the field positions for Canada as a whole (see Figure 4.6).

These findings indicate that, in general, Canada's research strengths at the field level are distributed across the four most research-intensive provinces. In contrast, important differences among these four provinces likely exist at the sub-field level. However, these differences could not be established with certainty because of the small number of papers in many of the 176 sub-fields at the provincial level.

Given these considerations, the positional analysis of research fields at the provincial level is perhaps most informative for provinces with smaller research enterprises, in which specific fields of strength are fewer in number and more readily distinguishable from the aggregated Canadian averages. Examples include Agriculture, Fisheries, and Forestry in Prince Edward Island and Manitoba; Historical Studies in New Brunswick; Earth and Environmental Sciences in Newfoundland and Labrador and Nova Scotia; and Biology in Saskatchewan.



Alberta



British Columbia

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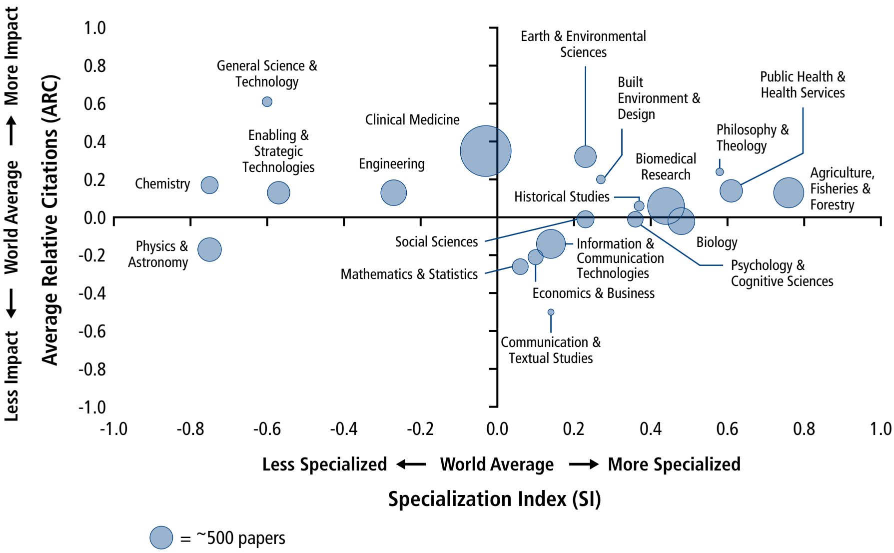
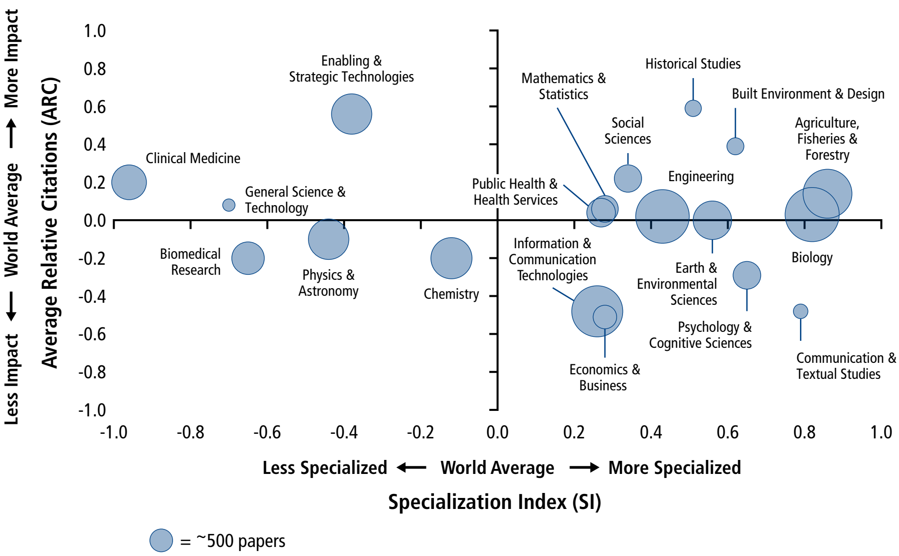


Manitoba



New Brunswick

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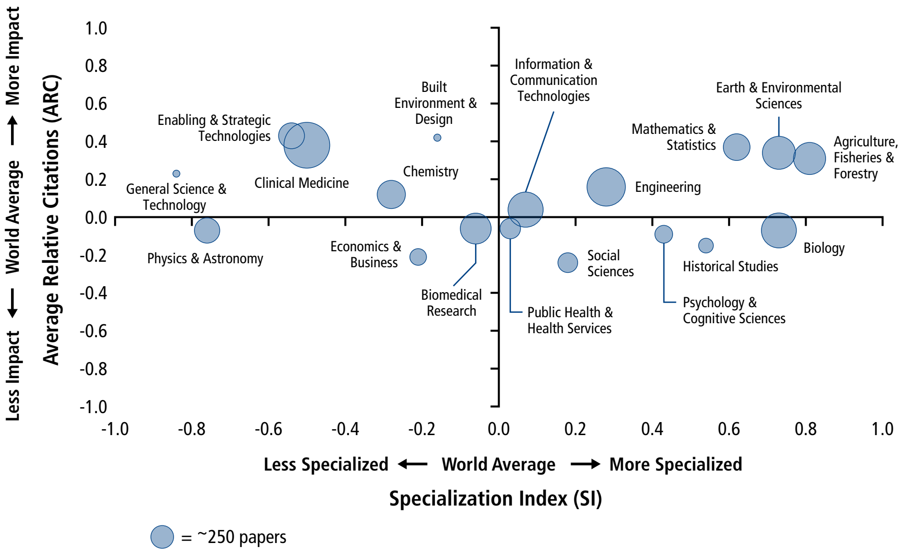
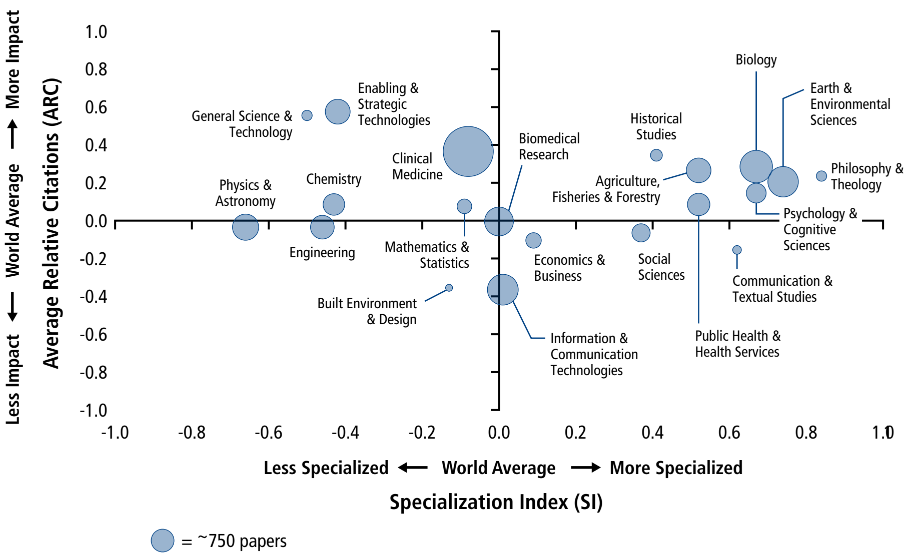


Newfoundland and Labrador



Nova Scotia

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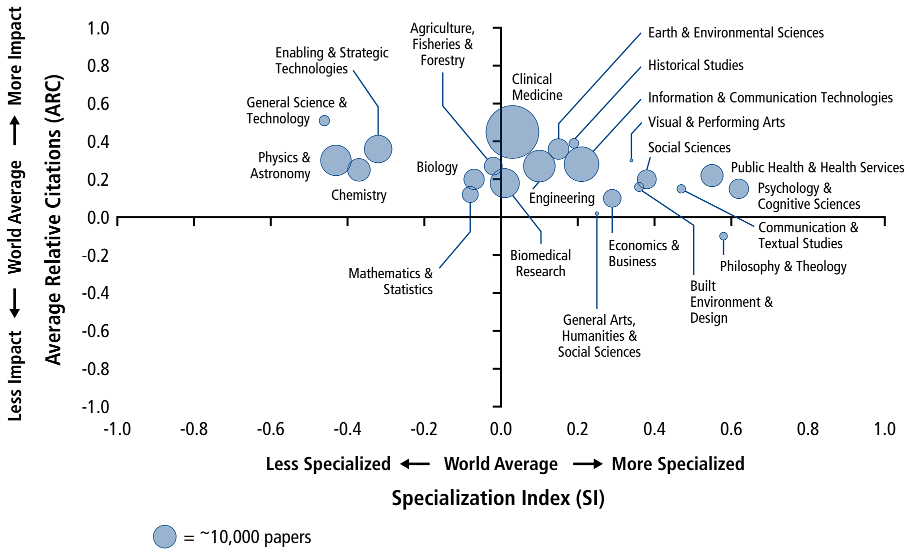
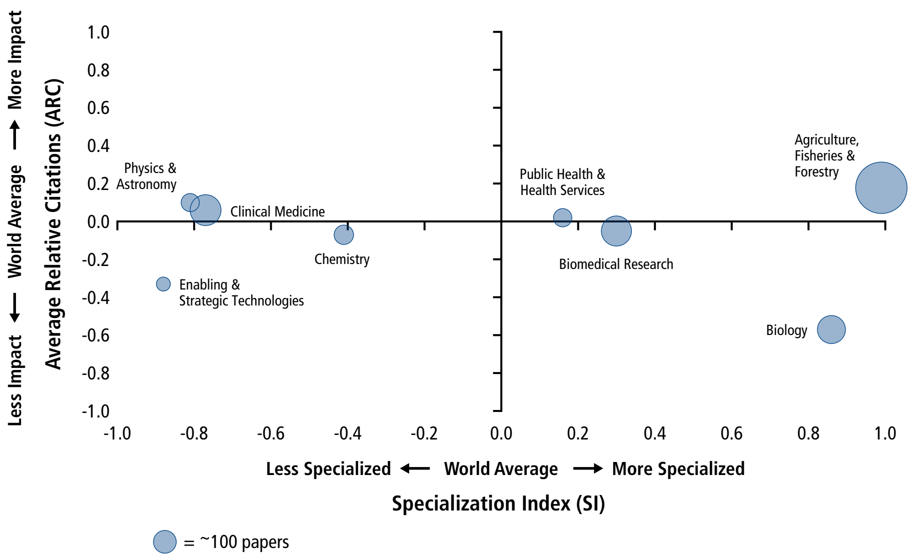


Ontario



Prince Edward Island

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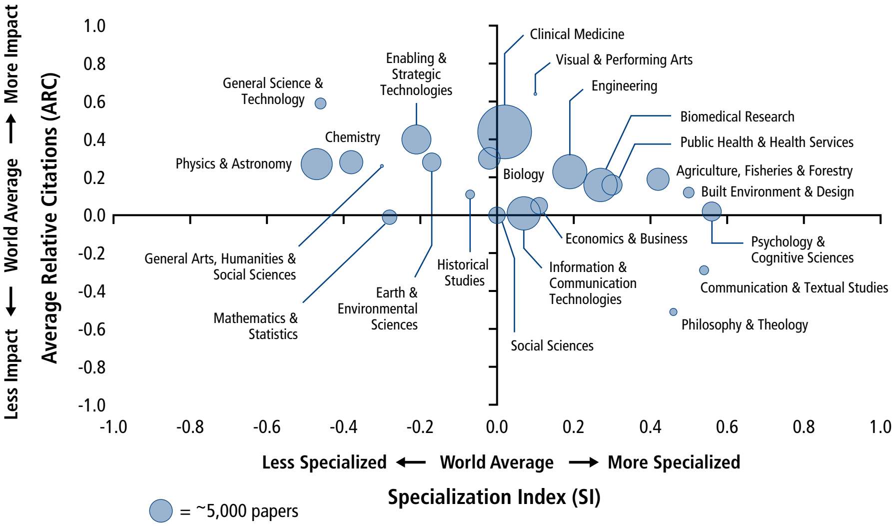
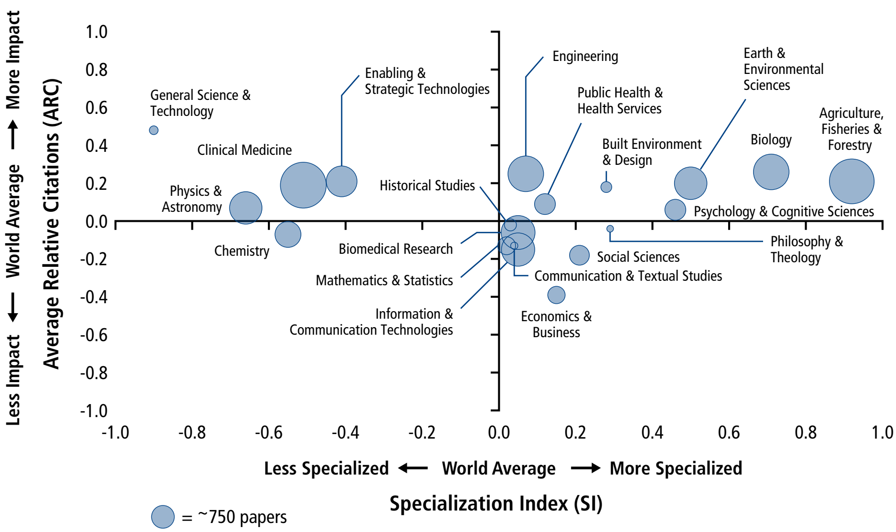


Quebec



Saskatchewan

Data source: Calculated by Science-Metrix using Scopus database (Elsevier)

Figure 9.4

Positional Analysis of Canadian Provinces in 22 Fields of Research, 1997–2010

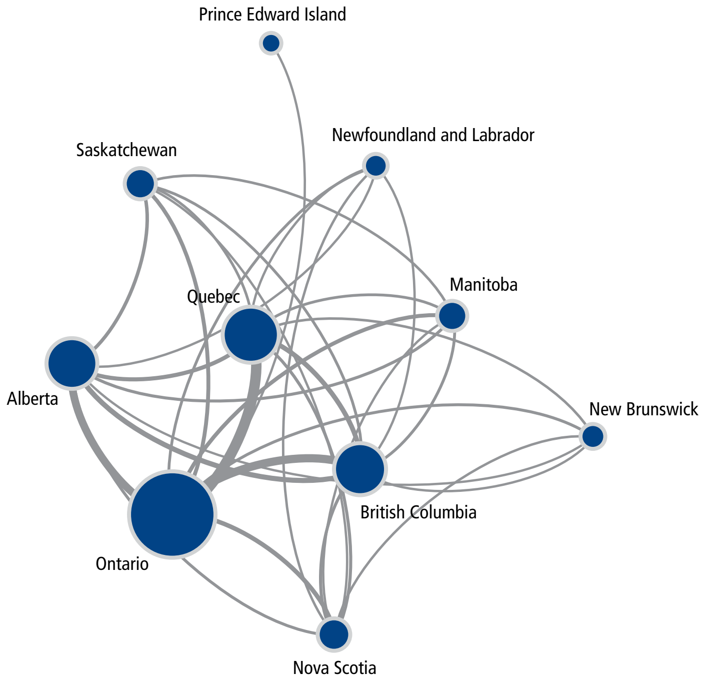
The size of the circles are differently scaled on each chart and relative size is indicated in the bottom-left corner. The circle size for each field is proportional to the number of publications included in the analysis. Fields with a positive value on the vertical axis (ARC) have an impact, on average that is above the world average. The horizontal axis (SI) is a measure of the proportion of publications in that discipline compared with the world average. ARC and SI scores are transformed in these figures to the hyperbolic tangent of the natural logarithm of the indicators in order to improve the readability of the figures and allow for a symmetrical representation of the data. The number zero is equal to the world average for both axes. Only the fields with more than 30 publications for the time period are shown.

9.3 COLLABORATION AMONG PROVINCES AND TERRITORIES

Collaboration among institutions, provinces, and sectors allows a larger number of researchers to have access to research infrastructure wherever it is located, and may promote the dissemination of research results (see Spotlight on Collaboration: ArcticNet). As noted in Chapter 6 with regard to international collaboration, larger jurisdictions tend to collaborate less externally. This trend also appears to be the case within Canada. Smaller provinces and territories have considerably higher inter-provincial collaboration rates than provinces with larger production volumes. Thus, Nunavut leads with a collaboration rate of 87 per cent (150 inter-provincial collaborations), which means that almost 9 out of every 10 papers from Nunavut are co-written with at least one researcher from another province or territory. The Northwest Territories ranks second with a collaboration rate of 80 per cent (close to 330 inter-provincial collaborations), and Yukon ranks third with a collaboration rate of 73 per cent (more than 200 inter-provincial collaborations).

In contrast, Quebec and Ontario have the lowest collaboration rates, of 15 per cent and 13 per cent respectively, but the largest numbers of inter-provincial collaborations in total (more than 24,000 and 44,000 papers respectively).

Ontario is the main hub in the Canadian collaboration network, with most provinces having their largest link with Ontario (see Figure 9.5). Ontario is particularly well connected to Quebec, British Columbia, and Alberta — the other leading provinces in scientific production. Not surprisingly, the largest link of the network is between Quebec and Ontario, the two provinces with the largest volume of scientific production. Apart from size, the factors underlying inter-provincial collaborations were not investigated for this report, but the location of national infrastructure facilities and the composition of national networks of S&T are probably of greater relevance than geographical proximity.



Data source: Calculated by Science-Metrix using Scopus database (Elsevier)

Figure 9.5

Collaboration Network of Canadian Provinces, 1997–2010

The size of the bubbles is proportional to the number of inter-provincial collaborations of a province, and the width of the links is proportional to the number of inter-provincial collaborations between two provinces. The data for the territories were too few to analyze.

Spotlight on Collaboration: ArcticNet

Although many inter-provincial collaborations emerge on an ad hoc basis, others are part of organized collaborative networks. In the last 20 years, the Networks of Centres of Excellence (NCE) program has invested over $1.5 billion[31] in networks that facilitate partnerships across sectors, scientific disciplines, and geographic jurisdictions.

ArcticNet is an NCE that brings together researchers and managers from the natural, health, and social sciences in several provinces and territories to study the impact

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31 http://www.nce-rce.gc.ca/About-APropos/Index_eng.asp.

of climate change in the Canadian Arctic. The network involves universities, Inuit organizations, Northern communities, and federal and provincial agencies, as well as industry and 100 partner organizations from 15 countries. ArcticNet researchers conduct research in projects across the Arctic, at sea including onboard the CCGS Amundsen, Canada's research icebreaker, a major infrastructure investment by the Canada Foundation for Innovation and the Department of Fisheries and Oceans Canada.

In 2010–2011, ArcticNet researchers conducted research across the Arctic, at more than 125 sites, including 35 Inuit communities. Research covers a wide spectrum of issues including understanding climate change, food security, coastal erosion, Inuit education, and emerging infectious diseases. Collaboration between researchers and Northern communities is key, and ArcticNet collaborates closely with Inuit Tapiriit Kanatami, the Inuit Circumpolar Council (Canada), and all four regional Inuit land claim organizations in developing and conducting its research program.

One of ArcticNet's major research collaborations with industry involves Imperial Oil Resources Ventures Limited and BP Exploration Operating Company Limited. ArcticNet researchers and their private-sector collaborators jointly collect environmental, geophysical, and geological data onboard the CCGS Amundsen in areas of the Beaufort Sea awarded exploration licences by the Government of Canada. Owned by ArcticNet, the new data are being made publicly available, thereby assisting industry with operational planning, and also benefitting regulators and the public.

ArcticNet's international collaboration has been enhanced by two new Canada Excellence Research Chairs (CERCs) at Université Laval and at the University of Manitoba. At Université Laval, the CERC led to the creation of the Canada-France Unité Mixte Internationale in Arctic sciences, facilitating Canada-France collaboration. The CERC at the University of Manitoba resulted in the creation of a new Arctic Science Partnership with the Greenland Climate Research Centre and Aarhus University in Denmark. The Partnership will share data, jointly hire scientists, and allow for the free flow of students between Denmark, Greenland, and Canada (ArcticNet, 2011).

9.4 S&T REPUTATIONS OF CANADA'S PROVINCES

The Survey of Canadian S&T Experts (see Section 2.2.3) asked each recipient to list the top three provinces in each of the 176 sub-fields. In general, respondents identified Ontario, Quebec, British Columbia, and Alberta as provinces of particular strength, but with variations among sub-fields. This finding correlates well with bibliometric evidence, in which the same four provinces have the largest research outputs, as well as investment levels.

9.5 TECHNOMETRIC RESULTS BY PROVINCE

Although not a great deal of information is available on technology development at a provincial level, patent data provide some insight into strengths related to applied research. Table 9.4 shows technometric indicators by province. Ontario leads in terms of total intellectual property (IP) ownership, accounting for over half of Canada's total number of patents in 2005–2010. Ontario also led the country in terms of patent citations, and was the only province with an increase in its patent ownership over the period. In contrast, Quebec is the only province with a positive flow of intellectual property, with a particularly strong performance in ICT, indicating that the province is accumulating more patents than it is producing.

Table 9.4

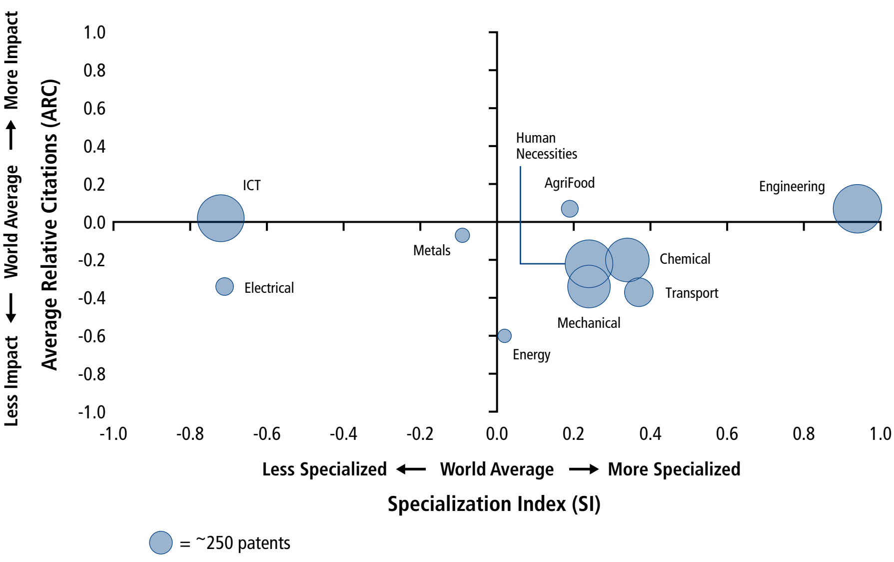
Technometric Indicators for Canadian Provinces and Territories

	2005–2010			1999–2004			
Province or Territory	IP (full counts)	IP (fractional counts)	ARC	IP (full counts)	IP (fractional counts)	ARC	Flow of IP
Ontario	8,042	7,891	1.08	7,805	7,555	0.96	-0.29
Quebec	4,489	4,433	0.98	5,527	5,405	1.08	0.21
British Columbia	1,733	1,696	0.94	2,031	1,967	0.92	-0.33
Alberta	1,465	1,434	0.92	1,630	1,573	0.86	-0.20
New Brunswick	86	84	0.83	103	95	0.73	-0.34
Saskatchewan	221	218	0.81	359	346	0.71	-0.39
Nova Scotia	123	118	0.61	130	122	0.71	-0.24
Manitoba	309	303	0.52	374	351	0.72	-0.10
Newfoundland and Labrador	27	26	–	39	36	0.92	-0.23
Prince Edward Island	9	9	–	13	12	–	–
Yukon	6	6	–	9	9	–	–
Northwest Territories	–	–	–	4	4	–	–

Data source: Calculated by Science-Metrix using data from the United States Patent and Trademark Office (USPTO)

The performance of Canadian provinces in technology development was determined through positional analysis of the 10 technometric fields listed in Chapter 7 (see Figure 9.6). As for previous figures of this type, the top-right quadrant contains patent classes in which the province had a high number of patents (relative to the world average) that were highly cited. These patent classes represent areas of technological strength in the province. The top-left quadrant indicates areas in which patents were highly cited (i.e., high impact), but in which the province had fewer patents than might be expected based on the world average. This quadrant can potentially be interpreted as identifying areas of opportunity. The bottom-left quadrant contains patent classes in which the province has both low levels of impact and low levels of output; and the bottom-right quadrant contains classes in which the province had a relatively high number of patents, but the patents were less cited than the world average. The size of the bubble indicates the overall number of Canadian patents in that area.

The analysis demonstrates particularly strong provincial performances in several patent classes, including AgriFood in Alberta, Manitoba, and Saskatchewan; Engineering in Alberta; Energy in British Columbia; ICT in Quebec; and Metals in Ontario.



Alberta

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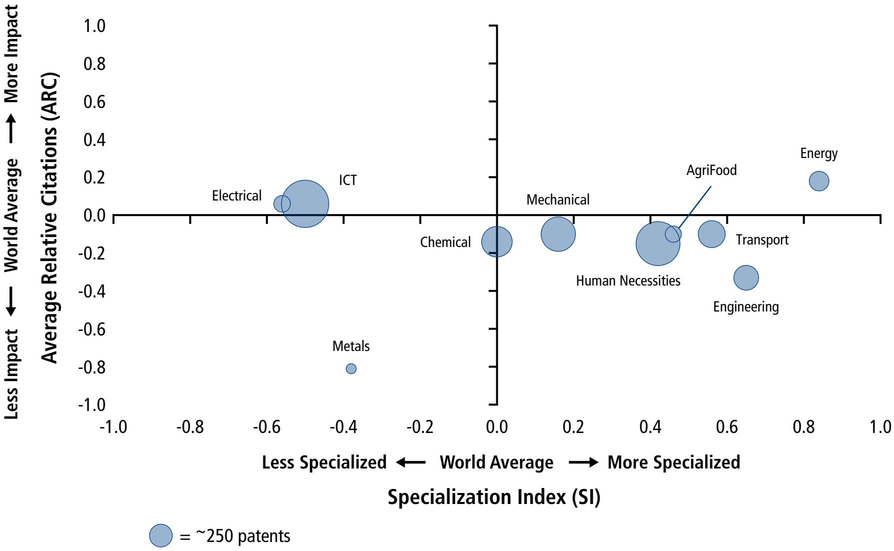
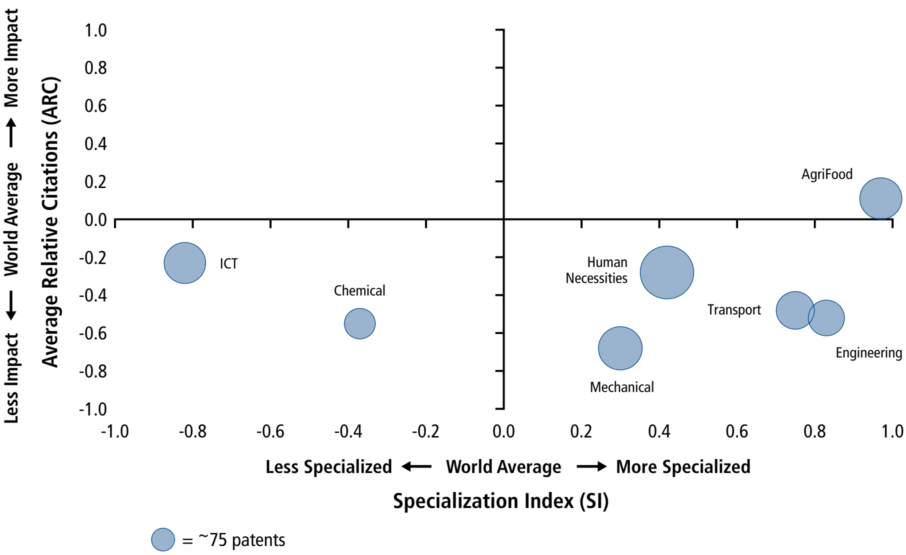


British Columbia



Manitoba

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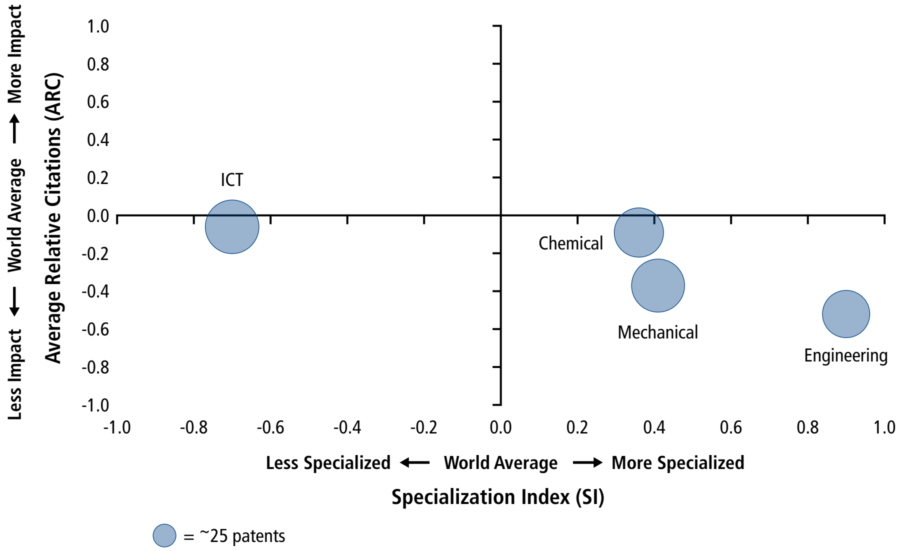
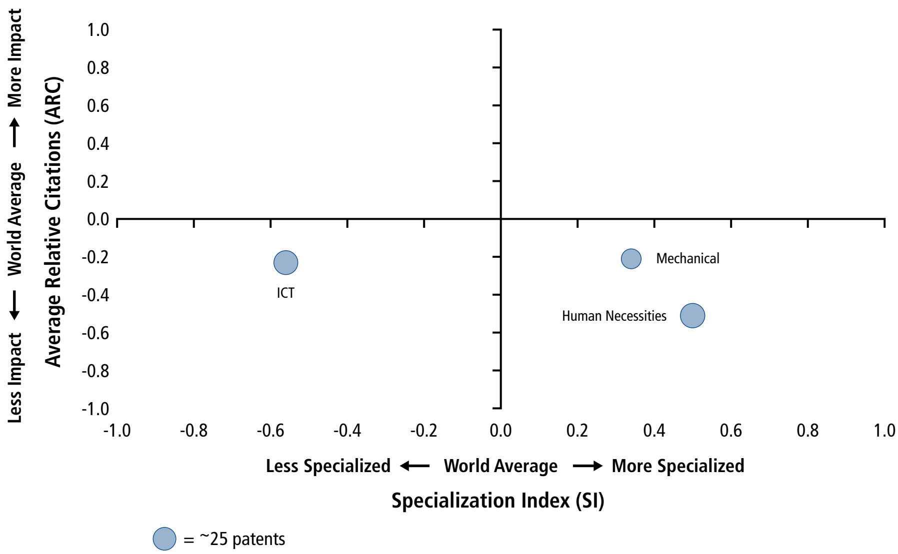


New Brunswick



Nova Scotia

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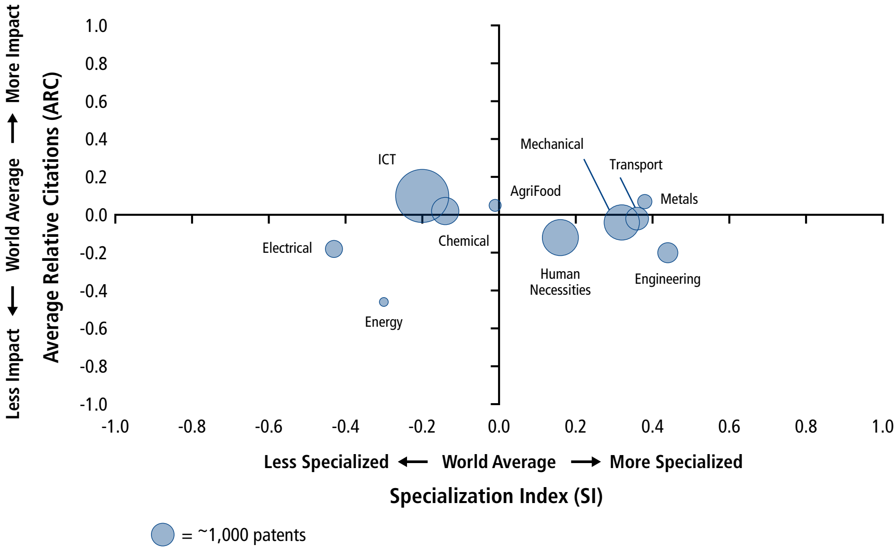
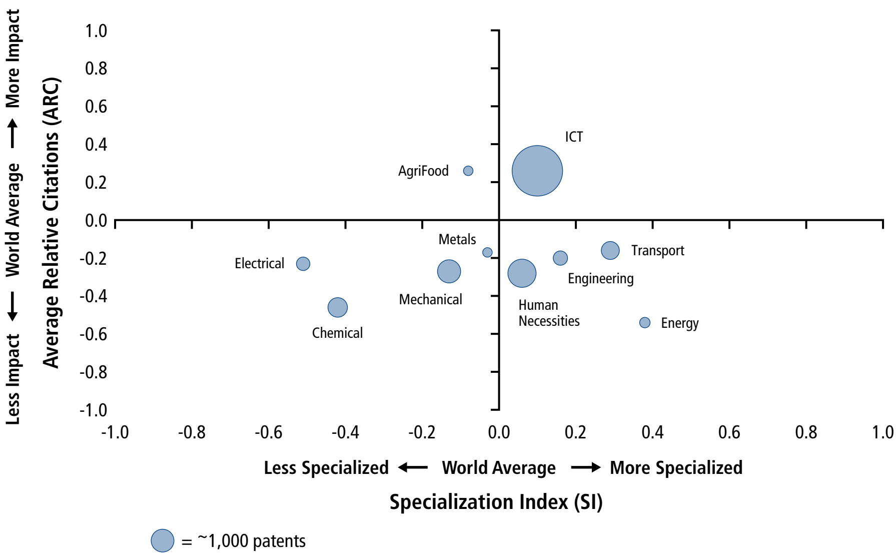


Ontario



Quebec

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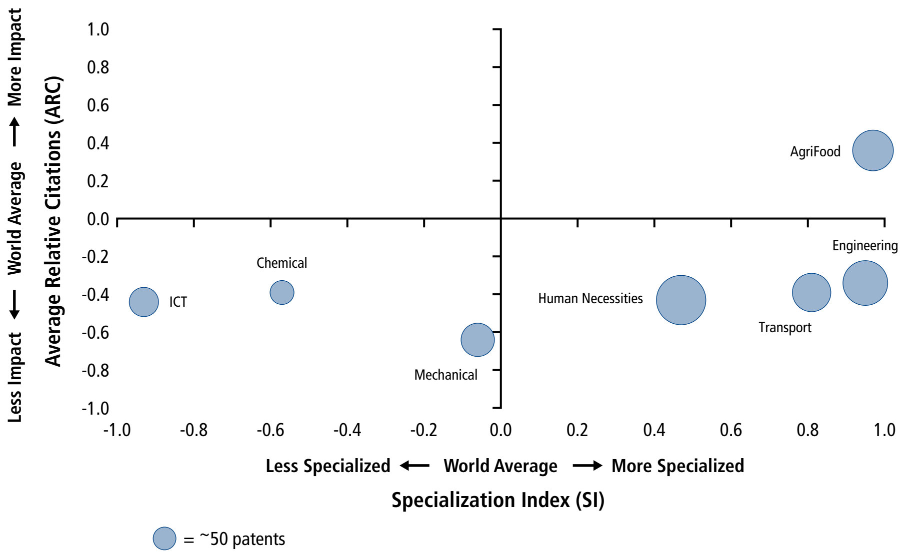


Saskatchewan

Data source: Calculated by Science-Metrix using data from the United States Patent and Trademark Office (USPTO)

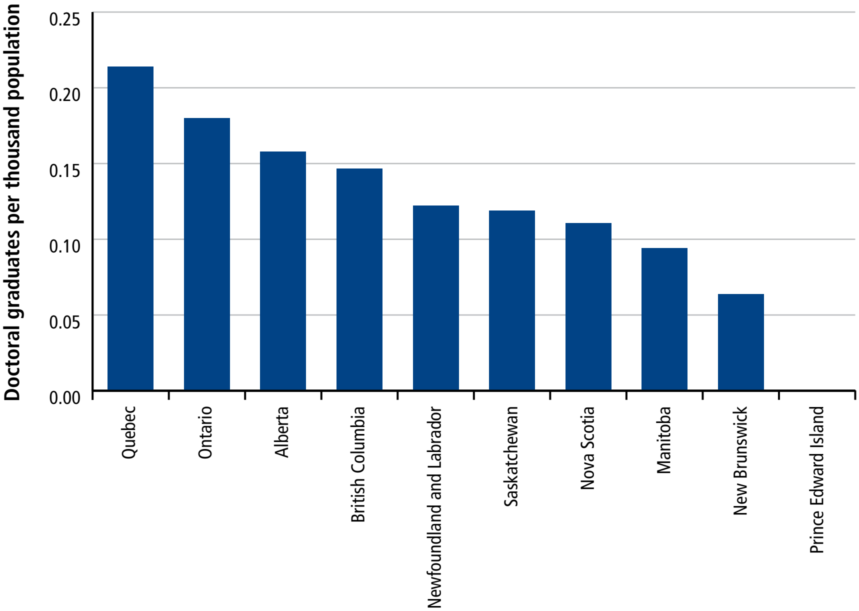
Figure 9.6

Positional Analysis of Canadian Provinces in 10 Fields of Patents Classification, 1997–2010

The sizes of the circles are scaled differently on each chart and relative size is indicated in the bottom-left corner. The circle size for each field is proportional to the number of patents included in the analysis. Areas with a positive value on the vertical axis have patents that are cited, on average, more than the world average. The horizontal axis is a measure of the proportion of patents in that area compared with the world average. ARC and SI scores are transformed in these figures to the hyperbolic tangent of the natural logarithm of the indicators in order to improve the readability of the figures and allow for a symmetrical representation of the data. The number zero is equal to the world average for both axes. Newfoundland and Labrador and Prince Edward Island did not have sufficient number of patents to calculate the graphs.

9.6 POST-SECONDARY GRADUATES BY PROVINCE

A highly skilled and educated workforce is a major determinant of S&T capacity. One measure of S&T capacity that is available at the provincial level is the number of doctoral students. As seen for other provincial measures, Ontario, Quebec, Alberta, and British Columbia are the strongest in absolute numbers and accounted for over 90 per cent of all doctoral graduates in Canada in 2009 (Statistics Canada, 2011d). Given the different sizes of provinces, however, a per capita measure is more meaningful (see Figure 9.7). Even by per capita measures the same four provinces have the highest numbers of doctoral graduates, probably reflecting the larger numbers of research-intensive universities in these provinces.



Note: The source data showed no doctoral graduates from PEI for 2009.
Data source: Statistics Canada (2011d); Statistics Canada (n.d.) CANSIM Table 051-0001

Figure 9.7
Doctoral Graduates per Thousand Population, 2009

9.7 COMPARISON WITH THE 2006 REPORT

Regional comparisons were not part of the 2006 report.

9.8 CONCLUSIONS

Ontario, Quebec, British Columbia, and Alberta are clearly the powerhouses of Canadian S&T by all metrics examined by the Panel. These four provinces accounted for 97 per cent of Canada's bibliometric output, with almost half coming from Ontario alone. The views of Canadian S&T experts on provincial strengths mirror the bibliometric findings, with Ontario, Quebec, British Columbia, and Alberta most often identified as provinces of strength, and Ontario most highly ranked in almost all sub-fields. The same four provinces also have the highest per capita numbers of doctoral graduating students. The Panel was not able to systematically analyze trend data at the provincial level, but saw nothing in the data to indicate that the dominance of these provinces in Canadian S&T is changing. Ontario, Quebec, British Columbia, and Alberta are distinct in producing world-class research in a number of fields, whereas the other provinces excel in a smaller number of fields, and specialization seems to be key. Differences in expenditure, which align with the results, likely contribute to the inter-provincial differences observed.

At the field level, some fields of research, particularly in Clinical Medicine, are strong in several Canadian provinces. The evidence presented in this chapter, however, also highlights provincial strengths that may not be evident in the nationally aggregated analyses: for example, the specialization of Manitoba and Prince Edward Island in Agriculture, Fisheries, and Forestry; and Saskatchewan in Biology. This diversity among provinces often aligns with local economic strengths and contributes to local and regional clusters of innovation.

10

Synthesis of Results

- Agriculture, Fisheries, and Forestry
- Biology
- Biomedical Research
- Built Environment and Design
- Chemistry
- Clinical Medicine
- Communication and Textual Studies
- Earth and Environmental Sciences
- Economics and Business
- Enabling and Strategic Technologies
- Engineering
- Historical Studies
- Information and Communication Technologies (ICT)
- Mathematics and Statistics
- Philosophy and Theology
- Physics and Astronomy
- Psychology and Cognitive Sciences
- Public Health and Health Services
- Social Sciences
- Visual and Performing Arts

10 Synthesis of Results

In response to the charge to the Panel (Chapter 1), Chapters 4 through 9 have presented evidence regarding the magnitude, quality, and trends of Canadian S&T. From this evidence, an integrated view emerges of the current status of each major field of Canadian S&T. This chapter presents a summary of these integrated findings on a field-by-field basis (in alphabetical order). Key data related to magnitude, quality, and trends are presented in Table 10.1 for the field level and in Table 10.2 for the sub-field level.

As described in Chapter 2, the fields used throughout this report are based on the best bibliometric classification system available to the Panel. This approach has facilitated the assessment of strengths using a number of different methodologies, and allows the integration of findings that is presented in this chapter. Limitations of the classification system are also noted in Chapter 2.

Table 10.1

Key S&T Indicators for All Fields

Field	MAGNITUDE/INTENSITY			QUALITY/IMPACT		
	# of papers (2005–2010)	Share of world pubs. (2005–2010) (%)	SI (2005–2010)	ARC score (2005–2010)	ARC rank (2005–2010)	Share of top 1% cited papers (%)
Agriculture, Fisheries & Forestry	15,880	5.33	1.38	1.25	8	7.90
Biology	18,227	5.23	1.18	1.34	7	5.45
Biomedical Research	31,326	4.96	1.12	1.18	9	4.22
Built Environment & Design	3,152	4.94	1.36	1.17	14	4.81
Chemistry	17,653	2.56	0.63	1.27	7	2.62
Clinical Medicine	88,354	4.09	0.98	1.59	3	6.15
Communication & Textual Studies	2,686	5.16	1.73	1.04	9	1.87
Earth & Environmental Sciences	15,788	5.79	1.23	1.29	9	4.53
Economics & Business	10,161	4.80	1.21	1.11	7	3.96
Enabling & Strategic Technologies	26,896	2.96	0.75	1.36	8	3.77
Engineering	34,927	3.92	1.01	1.37	6	4.44
Historical Studies	3,512	4.76	1.26	1.28	5	3.74
Information & Communication Technologies	40,529	4.35	1.12	1.30	6	4.27
Mathematics & Statistics	8,951	4.18	0.91	1.11	9	3.29
Philosophy & Theology	2,024	5.90	1.94	0.93	8	3.31
Physics & Astronomy	30,890	3.03	0.60	1.42	3	2.57
Psychology & Cognitive Sciences	12,319	7.64	1.96	1.13	5	5.39
Public Health & Health Services	15,298	6.88	1.82	1.24	7	8.00
Social Sciences	12,355	4.69	1.44	1.10	8	4.05
Visual & Performing Arts	286	3.71	1.37	2.09	2	4.55

	QUALITY/IMPACT			TRENDS				
	Canada's rank in survey of top-cited international researchers	% of top-cited researchers identifying Canada in top 5	% of Canadian S&T experts rating field as strong	Change in share of world pubs. (%)	Change in ARC	Change in SI	Gaining Ground (Canadian survey) (%)	Falling Behind (Canadian survey) (%)
	2	57	78	-0.98	0.00	-0.31	7	19
	5	37	57	-0.08	0.16	-0.11	5	16
	5	37	62	0.36	0.07	0.03	8	18
	5	29	50	-0.81	0.09	-0.26	10	7
	7	20	53	-0.04	0.04	-0.03	6	29
	4	43	55	0.40	0.10	0.04	7	16
	4	58	55	0.09	0.13	-0.03	21	14
	4	41	71	0.16	-0.02	-0.07	10	26
	3	63	66	-0.23	0.05	-0.12	14	6
	8	17	62	0.31	-0.05	0.06	13	21
	7	27	70	-0.47	0.16	-0.16	8	17
	5	35	53	0.21	-0.13	0.04	9	15
	4	42	64	-0.71	0.13	-0.20	5	12
	5	27	76	0.07	0.02	-0.01	24	15
	3	79	65	0.73	0.05	0.20	12	6
	7	19	56	0.34	0.16	0.05	8	10
	3	69	67	0.52	0.04	0.03	15	4
	3	58	65	0.78	0.07	0.18	26	10
	3	54	60	0.18	-0.05	0.05	12	11
	4	55	68	1.04	0.66	0.27	22	6

Notes: SI = Specialization Index; ARC = Average Relative Citations; ARC rank = Canada's rank by ARC for 2005–2010 (see Chapter 4 for full definitions of these indicators). Other variables are drawn from the Survey of Top-Cited International Researchers and the Survey of Canadian S&T Experts (see Chapter 5). "Trends" are for the period 2005–2010 compared with 1999–2004, except for "Gaining Ground" and "Falling Behind" which is for the past five years.

10.1 AGRICULTURE, FISHERIES, AND FORESTRY

Despite a substantial increase in research output (absolute number of papers) in Agriculture, Fisheries, and Forestry during the period 2005–2010 compared to the previous five years, Canada's share of world papers and its Specialization Index (SI) score in this field declined over the same time period. The impact of its publications, as assessed by Average Relative Citations (ARC), ranked eighth in the world, but remained static in 2005–2010 — at a time when Canada's overall ARC rose. Despite these bibliometric findings, the field shows many signs of strength: its share (7.9 per cent) of the world's top-cited papers in the field ranked second highest among all fields in Canada, and the ARC score of patents in AgriFood ranked first in the world.

Canada is very well regarded both internationally and nationally in Agriculture, Fisheries, and Forestry. It is ranked second in the world by top-cited international researchers, the highest of all fields, and classified as strong by 78 per cent of Canadian S&T experts. However, a higher percentage of Canadian S&T experts thought that it was falling behind (19 per cent) rather than gaining ground (7 per cent). The high international regard for the field is reflected in the fact that among recent doctoral graduates in Canada, Agriculture, Fisheries, and Forestry had the third-highest proportion of international students (over 23 per cent).

Two sub-fields stand out: Fisheries and Forestry. Fisheries research in Canada was ranked first in the world by top-cited researchers,[32] and this sub-field has a high output, accounting for 8.6 per cent of the world's papers. Canada's Forestry research was ranked second in the world by top-cited researchers, and Canada accounts for over 10 per cent of the world's papers in this sub-field. However, both Fisheries and Forestry declined between 1999–2004 and 2005–2010 in output and impact compared with the rest of the world. The only sub-field in the top three in the world by ARC rank is Dairy and Animal Science, which ranked third.

10.2 BIOLOGY

Canada's production of scientific papers in Biology remained fairly stable in 2005–2010 compared with the previous five years (both in terms of share of world papers and Specialization Index). During the same period, the field had a high and improving impact in terms of citations (ARC), ranking seventh in the world.

Canada is well regarded internationally in Biology, being ranked fourth in the world by top-cited researchers. Among Canadian S&T experts, 57 per cent felt

32 Based on a limited number of responses.

Canada was strong in Biology, but only 5 per cent thought it was gaining ground, a result that is somewhat inconsistent with other findings.

Three sub-fields of Biology show particular strengths: Evolutionary Biology, Ornithology, and Zoology. Evolutionary Biology is a large and growing sub-field, with 6.9 per cent of the world's papers in 2005–2010, an increase compared with 1999–2004. It ranks second in the world by ARC and was ranked fourth in the world by top-cited researchers. Ornithology is also a large field, accounting for 8.8 per cent of the world's papers. Its ARC rank is fourth in the world, and it was ranked first by top-cited international researchers.[33] Zoology is a much smaller field, with less than three per cent of world publications, but it has grown since 1999–2004 and has high impact, being ranked first in the world by ARC.

10.3 BIOMEDICAL RESEARCH

Biomedical Research increased both the quantity (share of world papers) and quality (ARC) of its scientific papers in 2005–2010 compared with the previous five years. The field is ranked ninth in the world by ARC. Several of the rapidly emerging clusters in Canada have keywords associated with biomedical research, indicating that the field is at the forefront of scientific development.

Canada is well regarded internationally in Biomedical Research, being ranked fifth in the world by top-cited international researchers. Among Canadian S&T experts, 62 per cent felt Canada was strong in this field compared with other advanced countries, although 18 per cent thought Canada was falling behind.

Among sub-fields, Anatomy and Morphology stands out as a particular strength. It is a small sub-field with 2.8 per cent of the world's papers, but has a very high ARC of 2.38, ranking it first in the world. Mycology and Parisitology ranks third in the world by ARC, and Toxicology ranks fifth.

10.4 BUILT ENVIRONMENT AND DESIGN

Canada's research output in Built Environment and Design is relatively small and is declining in terms of share of world papers and Specialization Index. In addition to low output, ARC scores place Canada 14th in the world, the lowest of any field. Canadian researchers, however, have a high level of international collaboration in Built Environment and Design, 39 per cent more than predicted by models.

33 Based on a limited number of responses.

Canada is moderately well regarded internationally in Built Environment and Design, being ranked fifth in the world by top-cited international researchers. Among Canadian S&T experts, 50 per cent felt Canada was strong in Built Environment and Design, and 10 per cent thought it was gaining ground. The field is attractive to international students who account for 14 per cent of its doctoral graduates in Canada.

Within the field of Built Environment and Design, the sub-field of Design Management and Practice is a particular strength. It is a moderately large sub-field, accounting for 4.7 per cent of the world's papers, and has a high ARC of 1.41 (third in the world).

10.5 CHEMISTRY

Chemistry accounts for a low share of Canada's total S&T output (based on its Specialization Index) and for a small share of the world output in this field. However, Canada's impact in Chemistry in terms of ARC improved slightly in 2005–2010, and places Canada seventh in the world. In addition, Chemicals account for eight per cent of Canada's patents, and the ARC score of those patents was second in the world.

Canada is moderately well regarded internationally in Chemistry, being ranked seventh in the world by top-cited international researchers. Among Canadian S&T experts, 53 per cent felt Canada was strong in Chemistry, but 29 per cent thought Canada was falling behind.

The strongest sub-field in Chemistry is Medicinal and Biomolecular Chemistry, which ranks sixth in the world by ARC and fifth by top-cited international researchers. Chemistry is perhaps the most homogeneous of all fields, with relatively small sub-fields that account for two to three per cent of world papers. With the exception of Medicinal and Biomolecular Chemistry, all have an ARC rank of seventh to ninth, and were ranked sixth to ninth by top-cited international researchers.

10.6 CLINICAL MEDICINE

Clinical Medicine is a very large field of Canadian research, accounting for over 22 per cent of Canada's scientific papers in 2005–2010. It is also growing; Canada's share of world papers increased significantly in 2005–2010 compared with the previous five years. The field has an extremely high and increasing impact, with an ARC that places Canada third in the world. As well as considerable strength within the country, Canadian researchers in Clinical Medicine also collaborate significantly with international colleagues, 57 per cent more than predicted by models.

Canada is well regarded internationally in Clinical Medicine, being ranked fourth in the world by top-cited international researchers. Among Canadian S&T experts, 55 per cent thought Clinical Medicine in Canada was strong, and 16 per cent said it was falling behind.

Clinical Medicine encompasses a large number of sub-fields, many of which show considerable strength. Particularly notable are the high ARC ranks of Dermatology and Venereal Diseases, and General and Internal Medicine (both ranked first in the world by ARC); Anesthesiology, Gastroenterology and Hepatology, and Orthopedics (all ranked second); and Surgery, and Urology and Nephrology (both ranked third). These sub-fields grew between 1999–2004 and 2005–2010 in terms of share of world papers, indicating that growth in Clinical Medicine is in areas of high-impact research.

10.7 COMMUNICATION AND TEXTUAL STUDIES

While maintaining its share of world output during the past decade, Communication and Textual Studies has increased in bibliometric impact, with an ARC score placing it ninth in the world in 2005–2010.

Canada is well regarded internationally in Communication and Textual Studies, ranked fourth in the world by top-cited international researchers. Among Canadian S&T experts, 55 per cent felt Canada was strong in Communication and Textual Studies, and 21 per cent thought it was gaining ground — one of the highest of any field and consistent with its rising ARC. The field accounts for the fourth largest group of university undergraduate students in Canada.

The sub-field of greatest strength in this field is Literary Studies. With 6.7 per cent of world papers, this sub-field was ranked first in the world by top-cited international researchers.[34] Despite the limitations of ARC scores in assessing these sub-fields, all rank moderately well, with Literary Studies ranked highest (ranked sixth in the world).

34 Based on a limited number of responses.

10.8 EARTH AND ENVIRONMENTAL SCIENCES

Although Canada's share of world papers in Earth and Environmental Sciences remained stable in 2005–2010 compared with the previous five years, the field's ARC and Specialization Index experienced either no growth or negative growth in the past five years. The ARC score places Canada ninth in the world. In terms of patents, the category of Metals lost ground in both size and impact in 2005–2010 compared with 1999–2004, with ARC falling from 5th to 11th in the world. In contrast, among the bibliometric research clusters with a high Specialization Index, and among the most interdisciplinary clusters, several were associated with Earth and Environmental Sciences.

Canada is well regarded internationally in Earth and Environmental Sciences, being ranked fourth in the world by top-cited international researchers. Among Canadian S&T experts, 71 per cent felt Canada was strong in the field, but 26 per cent thought it was losing ground, consistent with the bibliometric and technometric findings. The field attracts large numbers of international researchers, with international students comprising 26 per cent of doctoral graduates and visa holders accounting for 6.5 per cent of faculty researchers.

Within the field of Earth and Environmental Sciences, the sub-field of Environmental Sciences is the smallest in terms of share of world papers (4.81 per cent in 2005–2010, a decline since 1999–2004). However, this sub-field was ranked fourth in the world in terms of ARC and by top-cited international researchers. In contrast, the sub-fields of the earth sciences are typically large, but of low impact, with ARC rankings 10th in the world or lower, despite being ranked fourth to seventh by top-cited international researchers. For example, the sub-field of Geology accounted for 10.5 per cent of the world's publications, but ranked 14th in the world in terms of ARC.

10.9 ECONOMICS AND BUSINESS

Economics and Business is one of the most stable fields in bibliometric terms. It experienced a slight decrease in output (both Specialization Index and share of world papers) but a slight increase in impact (ARC) in 2005–2010 compared with the previous five years. The ARC score places Canada seventh in the world in this field.

Canada is very well regarded internationally in Economics and Business, being ranked third in the world by top-cited international researchers. Among Canadian S&T experts, 66 per cent felt Canada was strong in the field, and 14 per cent thought it was gaining ground. Economics and Business produces the largest numbers of graduates at both the college and master's levels of all fields in Canada, and the second-largest number of university undergraduates.

All sub-fields of Economics and Business produce a large amount of research, ranging from 4.1 to 7.9 per cent of the world's papers. In terms of impact, Business and Management ranked first in the world by ARC. Logistics and Transportation ranked third and Economic Theory ranked fourth. Canada's reputation among top-cited international researchers is particularly high in the sub-fields of Agricultural Economics and Policy, and Logistics and Transportation, both ranked first in the world.[35]

10.10 ENABLING AND STRATEGIC TECHNOLOGIES

Although Canada's bibliometric output in Enabling and Strategic Technologies is increasing (both in Specialization Index and share of world papers), it remains low. The impact of this research (ARC score) is high, but slightly lower in 2005–2010 than in the previous five years, placing Canada eighth in the world. The field is associated with clusters that are rapidly emerging (carbon nanotubes) and highly specialized (oil sands).

Canada is regarded only modestly internationally in Enabling and Strategic Technologies, being ranked eighth in the world by top-cited international researchers. This ranking may reflect the field's low output. Among Canadian S&T experts, 62 per cent felt Canada was strong in Enabling and Strategic Technologies, but 21 per cent thought it was falling behind.

Because the sub-fields that make up Enabling and Strategic Technologies are extremely heterogeneous — ranging from Bioinformatics to Energy to Strategic, Defence, and Security Studies — large differences might be expected in performance at the sub-field level. However, this is not the case. All sub-fields have a moderate output, ranging from 1.9 to 4.9 per cent of world papers, and moderate ARC and survey rankings, with the highest ARC rank in Optoelectronics and Photonics (fourth). In light of its strategic importance, the sub-field of Energy is of particular relevance. Research in this sub-field ranked seventh in the world in terms of ARC, and ranked fourth in the world by top-cited international researchers.[36] Energy was also seventh in the world in terms of patent citations, a decline over the past five years.

35 Based on a limited number of responses.

36 Based on a limited number of responses.

10.11 ENGINEERING

Engineering is the third-largest field as measured by bibliometric output. Although the number of papers increased dramatically in 2005–2010 compared with the previous five years, Canada's share of world papers and Specialization Index fell, possibly reflecting the tremendous increase in output in this field by China. In contrast to falling output, the impact in terms of ARC rose from 1.21 to 1.37. Several of the rapidly emerging clusters in Canada are associated with Engineering, indicating the ongoing evolution of this field. Engineering accounts for six per cent of Canada's patents, the ARC score of which places Canada fifth in the world.

Canada is moderately well regarded internationally in Engineering, being ranked seventh in the world by top-cited international researchers. Among Canadian S&T experts, 70 per cent felt Canada was strong in Engineering, but 17 per cent thought it was falling behind. Consistent with its large bibliometric output, Engineering produces the largest number of doctoral graduates among all fields in Canada (16.8 per cent), 18 per cent of whom are international students.

Automobile Design and Engineering is a particularly strong sub-field of Engineering. Canadian research in this sub-field accounted for 8.4 per cent of the world's total in 2005–2010, having grown substantially since 1999–2004, and its ARC of 1.49 ranked third in the world. Industrial Engineering and Automation also ranked third in the world by ARC (although its share of world publications declined), and Electrical and Electronic Engineering, and Mining and Metallurgy, both ranked fifth by ARC and sixth by top-cited international researchers.

10.12 HISTORICAL STUDIES

Canada's share of world papers in Historical Studies increased slightly in 2005–2010 compared to the previous five years, but its impact (based on ARC score) decreased. Nevertheless, Canadian research in Historical Studies remains highly cited and ranks fifth in the world by ARC.

Canada is well regarded internationally in Historical Studies, being ranked fifth in the world by top-cited international researchers. Among Canadian S&T experts, 53 per cent thought Canada was strong in Historical Studies, but 15 per cent felt it was losing ground.

Historical Studies is a heterogeneous field, encompassing several sub-fields that span the humanities, social sciences, and natural sciences. Despite this heterogeneity, the size of sub-fields is remarkably consistent, producing 4.1 to 5.4 per cent of world papers. Based on bibliometrics, sub-fields of strength in Historical Studies include Classics (ranked first in the world by ARC); History of Social Sciences (ranked second); and History of Science, Technology, and Medicine (ranked fourth).

10.13 INFORMATION AND COMMUNICATION TECHNOLOGIES (ICT)

The field of ICT represents a major research enterprise in Canada. It accounted for over 10 per cent of the nation's output of scientific papers in 2005–2010 (the second-largest field in Canada), despite a decrease in both Canada's share of world papers in the field, compared to 1994–2004, and in the Specialization Index. ICT also has a high impact, with an ARC ranking that is sixth in the world.

Several rapidly emerging research clusters in Canada are associated with ICT, including clusters in networking and wireless technologies, information processing and computerization, speech recognition and other biometric technologies, and advanced data analysis. ICT accounts for 44 per cent of Canada's patents, with an ARC score that is third-highest in the world. Canadian researchers in ICT are highly involved in international collaborations, at a level that is 40 per cent higher than expected from a prediction model.

Canada is well regarded internationally in ICT, being ranked fourth in the world by top-cited international researchers. Among Canadian S&T experts, 64 per cent considered the field to be strong in Canada. Sixteen per cent of recent doctoral graduates in ICT in Canada were international students.

Medical Informatics is the strongest sub-field within ICT. It is a large sub-field, with Canadian research accounting for 8.1 per cent of the world's papers in 2005–2010, an increase since 1999–2004. Canadian research in Medical Informatics ranks second in the world by ARC, and fourth by top-cited international researchers.[37] Other sub-fields of strength in ICT include Information Systems (ranked third by ARC and by top-cited international researchers); and Computer Hardware and Architecture, and Networking and Telecommunications (both ranked fourth by ARC).

37 Based on a limited number of responses.

10.14 MATHEMATICS AND STATISTICS

Mathematics and Statistics had stable bibliometric output and impact between the periods 1999–2004 and 2005–2010, and is now ranked ninth in the world by ARC. Canadian researchers in the field have a high level of collaboration internationally that is 47 per cent greater than predicted by models.

Canada is well regarded internationally in Mathematics and Statistics, being ranked fifth in the world by top-cited international researchers. Among Canadian S&T experts, 76 per cent felt Canada was strong in Mathematics and Statistics, and 24 per cent thought Canada was gaining ground, the second highest of any field. Aligned with this strong reputation is the attractiveness of Canada to international students who comprise 25 per cent of doctoral graduates in the field.

Sub-fields of Mathematics and Statistics have a moderate level of output, impact, and reputation. In terms of ARC, the strongest sub-field is General Mathematics (ranked fifth in the world), but Statistics and Probability has the highest reputation (ranked third in the world by top-cited international researchers), and is the largest field, producing 7.1 per cent of world papers.

10.15 PHILOSOPHY AND THEOLOGY

As measured by bibliometrics, Philosophy and Theology has a very high and increasing output (both by Specialization Index and share of world papers), but relatively low (though increasing) impact (eighth in the world by ARC). Canada is very well regarded internationally in Philosophy and Theology, being ranked third in the world by top-cited international researchers. In addition, 65 per cent of Canadian S&T experts felt Canada was strong in Philosophy and Theology, and 12 per cent consider that Canada was gaining ground.

Among sub-fields of Philosophy and Theology, Religions and Theology ranked fifth in the world by ARC, and Applied Ethics and Philosophy were both ranked third by top-cited international researchers.[38]

10.16 PHYSICS AND ASTRONOMY

Physics and Astronomy accounted for over seven per cent of Canada's scientific papers in 2005–2010, the fifth-largest field as measured by bibliometric output. However, Canada's output relative to the rest of the world, and its Specialization Index, is low although it is increasing. The impact of research in this field is

38 Based on a limited number of responses.

extremely high with an ARC ranking that increased in 2005–2010 compared with the previous five years, placing Canada third in the world. In addition, several high-impact and rapidly emerging clusters in Canada are associated with Physics and Astronomy.

Canada is moderately well regarded internationally in Physics and Astronomy, being ranked seventh in the world by top-cited international researchers. Similarly, among Canadian S&T experts, 56 per cent felt Canada was strong in Physics and Astronomy, but only 8 per cent thought it was gaining ground.

International and Canadian experts identified several infrastructure facilities associated with Physics and Astronomy that are an advantage for Canada, including the Canadian Light Source synchrotron, the Sudbury Neutrino Observatory/Laboratory, TRIUMF (Canada's national laboratory for particle and nuclear physics), and the Perimeter Institute for Theoretical Physics.

There is considerable variation in the performance of sub-fields in Physics and Astronomy. Astronomy and Astrophysics as well as Nuclear and Particle Physics ranked first in the world by ARC. However, the performance of other sub-fields was less impressive. Like the field as a whole, the reputation of the sub-fields among top-cited international researchers is generally lower than would be expected based on ARC scores, possibly reflecting the relatively low output in several sub-fields.

10.17 PSYCHOLOGY AND COGNITIVE SCIENCES

In the field of Psychology and Cognitive Sciences, Canada has both an extremely high output (7.6 per cent of world publications) and a high impact (with an ARC ranking that is fifth in the world). Both output and impact increased in 2005-2010 compared with the previous five years.

Canada is very well regarded internationally in Psychology and Cognitive Sciences, being ranked third in the world by top-cited international researchers. Among Canadian S&T experts, 67 per cent felt Canada was strong in Psychology and Cognitive Sciences, and 15 per cent thought it was gaining ground in the field.

Psychology and Cognitive Sciences is one of the six largest fields in Canada in terms of undergraduate university education, and it accounts for nine per cent of all doctoral graduates in Canada.

The sub-fields of Psychology and Cognitive Sciences span the health sciences as well as the natural and social sciences, each of which has its own standards by which to assess excellence. However, in terms of reputation, Psychoanalysis was ranked first in the world, and Clinical Psychology, Developmental and Child Psychology, and Experimental Psychology were each ranked third by top-cited international researchers.[39] General Psychology and Cognitive Sciences was ranked second in the world by ARC, and Clinical Psychology fourth.

10.18 PUBLIC HEALTH AND HEALTH SERVICES

Public Health and Health Services is a large and rapidly growing field in Canada, accounting for close to seven per cent of world output in the field. Its ARC increased in 2005–2010 compared with the previous five years, and places it seventh in the world. Furthermore, Canada produces eight per cent of the world's top-cited papers in Public Health and Health Services, the highest percentage of any field in the country.

Canada is very well regarded internationally in Public Health and Health Services, being ranked third in the world by top-cited international researchers. Among Canadian S&T experts, 65 per cent considered Canada strong in Public Health and Health Services, and 26 per cent felt Canada was gaining ground, the highest of any field. Public Health and Health Services educates a large number of students at the college and university undergraduate and master's levels, but a relatively small number at the doctoral level, of whom only four per cent are international students.

All sub-fields in Public Health and Health Services have a high output, with Canadian research accounting for 5.3 to 8.3 per cent of research papers in the world. Two sub-fields, Speech-Language Pathology and Audiology, and Substance Abuse, were ranked first in the world by top-cited international researchers.[40] Speech-Language Pathology and Audiology also ranked third in the world by ARC.

10.19 SOCIAL SCIENCES

Canada's output in the Social Sciences increased slightly in 2005–2010 compared with the previous five years (both in share of world papers and Specialization Index). Its impact, however, decreased slightly over the same period, placing it eighth in the world by ARC.

39 Based on a limited number of responses.

40 Based on a limited number of responses.

Canada is very well regarded internationally in Social Sciences, being ranked third in the world by top-cited international researchers. Among Canadian S&T experts, 60 per cent felt Canada was strong in Social Sciences.

The field of Social Sciences plays a very large role in student education in Canada. It accounts for 25 per cent of all university undergraduates as well as 23 per cent of master's graduates and 15 per cent of doctoral graduates, of whom 10 per cent are international students.

The field of Social Sciences encompasses a large range of sub-fields, with a considerable range of performance. Gender Studies and Social Work were ranked first in the world by top-cited international researchers,[41] and Criminology ranked first in the world by ARC.

10.20 VISUAL AND PERFORMING ARTS

Visual and Performing Arts is the smallest field in Canada, as measured by bibliometric output, but is growing both in terms of Canada's share of world papers and Specialization Index, with the highest Growth Index of any field. Its impact, based on ARC scores, is the highest of all fields and rising, placing Canada second in the world in 2005–2010. Canadian researchers also collaborate significantly in Visual and Performing Arts, 83 per cent more than predicted by a model, the highest of all fields.

Canada is well regarded internationally in Visual and Performing Arts, being ranked fourth in the world by top-cited international researchers. Among Canadian S&T experts, 68 per cent felt Canada was strong in Visual and Performing Arts and 22 per cent thought it was gaining ground in the field, one of the highest of any field.

Because of the relatively small number of published papers, and low numbers of responses in the surveys in each of the sub-fields of Visual and Performing Arts, particular sub-fields of strength could not be reliably identified.

41 Based on a limited number of responses.

Table 10.2

Key S&T Indicators for All 176 Sub-Fields

		MAGNITUDE/INTENSITY		
Field	Sub-Field	# of papers (2005–2010)	Share of world pubs. (2005–2010) (%)	SI (2005–2010)
Agriculture, Fisheries & Forestry	Agronomy & Agriculture	3,300	4.47	1.20
	Dairy & Animal Science	2,091	4.11	1.01
	Fisheries	2,406	8.59	2.03
	Food Science	1,862	3.85	0.95
	Forestry	3,301	10.40	2.96
	Horticulture	391	4.29	1.09
	Veterinary Sciences	2,529	4.51	1.18
Biology	Ecology	5,238	7.23	1.67
	Entomology	1,752	4.99	1.24
	Evolutionary Biology	2,965	6.86	1.43
	Marine Biology & Hydrobiology	2,720	5.52	1.20
	Ornithology	766	8.80	1.93
	Plant Biology & Botany	4,156	3.52	0.82
	Zoology	630	2.93	0.60
Biomedical Research	Anatomy & Morphology	251	2.80	0.59
	Biochemistry & Molecular Biology	7,738	4.93	1.16
	Biophysics	1,486	4.82	1.13
	Developmental Biology	4,862	5.57	1.17
	Genetics & Heredity	1,797	6.66	1.24
	Microbiology	5,430	4.16	0.94
	Microscopy	258	3.49	0.83
	Mycology & Parasitology	764	3.73	0.77
	Nutrition & Dietetics	1,910	4.42	1.11
	Physiology	2,793	9.59	2.37
	Toxicology	1,858	4.29	0.99
	Virology	2,179	4.66	1.00
Built Environment & Design	Architecture	51	2.32	0.90
	Building & Construction	1,271	4.42	1.17
	Design Practice & Management	902	4.68	1.27
	Urban & Regional Planning	928	6.89	1.95

	QUALITY/IMPACT				TRENDS		
	ARC score (2005–2010)	ARC rank (2005–2010)	International survey rank	% of Canadian survey respondents rating sub-field as strong	Change in share of world pubs. (%)	Change in ARC	Change in SI
	1.18	10	4	77	-1.65	0.08	-0.49
	1.64	3	3	68	-0.64	0.23	-0.19
	1.31	6	1	80	-1.18	-0.11	-0.46
	1.13	7	5	59	-0.44	-0.01	-0.18
	1.12	12	2	76	-1.95	-0.06	-0.60
	0.76	17	9	40	0.29	-0.23	-0.03
	1.31	5	3	60	0.02	-0.03	0.05
	1.41	7	4	60	-0.54	0.30	-0.28
	1.20	7	11	29	-0.40	0.13	-0.13
	1.42	2	4	57	1.12	0.01	0.17
	1.30	6	5	68	1.24	0.02	0.21
	1.31	4	1	24	0.61	-0.02	-0.10
	1.28	9	9	67	-0.80	0.21	-0.26
	1.48	1	4	43	0.56	-0.31	0.07
	2.38	1	4	20	-0.21	1.09	-0.14
	1.11	9	5	74	0.20	0.03	0.04
	0.99	11	5	44	0.51	-0.06	0.14
	1.07	10	4	62	0.93	0.01	0.18
	1.31	7	7	80	0.90	0.09	0.00
	1.28	7	6	61	0.31	0.10	0.00
	0.90	12	6	32	-0.66	-0.16	-0.20
	1.55	3	6	28	0.36	0.32	0.03
	1.41	6	5	39	0.10	0.27	-0.01
	0.94	13	5	44	0.97	-0.04	0.18
	1.35	5	6	28	0.08	0.01	-0.03
	1.17	8	6	63	0.81	0.11	0.09
	–	–	6	41	1.06	–	0.47
	1.24	11	6	59	-0.96	-0.13	-0.32
	1.41	3	10	45	-0.91	0.41	-0.26
	0.86	17	8	41	-0.31	0.05	-0.13

continued on next page

Field	Sub-Field	MAGNITUDE/INTENSITY # of papers (2005–2010)	Share of world pubs. (2005–2010) (%)	SI (2005–2010)
Chemistry	Analytical Chemistry	2,881	2.71	0.68
	General Chemistry	2,222	2.45	0.61
	Inorganic & Nuclear Chemistry	1,946	1.98	0.44
	Medicinal & Biomolecular Chemistry	1,598	2.18	0.50
	Organic Chemistry	3,851	2.88	0.75
	Physical Chemistry	2,057	2.85	0.65
	Polymers	3,098	2.67	0.66
Clinical Medicine	Allergy	553	3.68	0.80
	Anesthesiology	1,898	4.89	1.35
	Arthritis & Rheumatology	1,665	5.31	1.13
	Cardiovascular System & Hematology	7,166	4.69	1.11
	Complementary & Alternative Medicine	207	2.72	0.66
	Dentistry	1,362	2.70	0.62
	Dermatology & Venereal Diseases	915	1.78	0.41
	Emergency & Critical Care Medicine	1,653	5.31	1.31
	Endocrinology & Metabolism	3,821	5.11	1.18
	Environmental & Occupational Health	469	3.84	1.02
	Gastroenterology & Hepatology	2,382	3.04	0.72
	General & Internal Medicine	5,824	3.05	0.74
	General Clinical Medicine	660	2.76	0.64
	Geriatrics	794	5.45	1.38
	Immunology	4,401	4.46	0.94
	Legal & Forensic Medicine	291	3.03	0.83
	Neurology & Neurosurgery	11,954	4.99	1.17
	Nuclear Medicine & Medical Imaging	4,621	4.63	1.18
	Obstetrics & Reproductive Medicine	2,609	3.33	0.81
	Oncology & Carcinogenesis	7,270	4.15	0.92
	Ophthalmology & Optometry	1,592	2.85	0.72
	Orthopedics	2,773	4.42	1.08
	Otorhinolaryngology	1,176	3.16	0.91
	Pathology	1,278	4.50	0.99
	Pediatrics	2,472	4.30	1.12
	Pharmacology & Pharmacy	3,678	3.02	0.75
	Psychiatry	4,234	5.73	1.44

QUALITY/IMPACT				TRENDS		
ARC score (2005–2010)	ARC rank (2005–2010)	International survey rank	% of Canadian survey respondents rating sub-field as strong	Change in share of world pubs. (%)	Change in ARC	Change in SI
1.20	9	7	40	-0.24	-0.06	-0.10
1.59	6	7	39	-0.28	0.23	-0.09
1.23	9	7	58	-0.11	0.02	-0.04
1.26	6	5	51	-0.06	0.01	-0.05
1.15	7	8	63	0.21	-0.02	0.05
1.03	9	9	58	0.51	-0.04	0.13
1.43	8	7	44	-0.11	0.14	-0.06
1.46	9	3	43	0.49	0.17	-0.04
1.87	2	2	24	0.70	0.30	0.20
1.58	7	6	53	1.06	-0.15	0.10
1.42	8	5	91	0.61	-0.04	0.08
1.36	7	–	18	0.53	-0.16	0.06
1.07	11	6	15	-0.33	0.01	-0.09
2.24	1	11	17	0.15	0.47	0.01
1.55	7	3	58	0.67	0.03	0.10
1.29	9	4	76	0.02	0.14	-0.04
1.68	7	–	32	0.60	0.20	0.21
2.09	2	8	44	0.03	0.57	-0.07
3.93	1	3	54	0.13	0.67	-0.02
1.39	5	3	52	-0.25	-0.28	-0.14
1.19	12	3	62	0.14	0.00	-0.05
1.09	6	9	69	0.65	0.04	0.04
0.94	13	1	8	0.03	-0.37	0.02
1.48	6	4	79	0.17	0.12	-0.01
1.23	7	10	58	1.26	-0.06	0.32
1.59	4	6	53	0.08	0.15	-0.05
1.31	6	5	83	0.50	0.03	0.05
0.98	12	5	34	-0.13	-0.03	-0.06
1.49	2	2	43	0.73	-0.10	0.12
1.47	4	11	17	0.59	0.02	0.19
1.37	7	4	31	1.22	0.05	0.24
1.55	5	3	64	1.07	-0.08	0.27
1.33	7	7	44	-0.25	0.03	-0.11
1.25	5	3	26	0.57	-0.01	0.04

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Field	Sub-Field	MAGNITUDE/INTENSITY # of papers (2005–2010)	Share of world pubs. (2005–2010) (%)	SI (2005–2010)
Clinical Medicine *(continued)*	Respiratory System	2,854	5.40	1.32
	Sport Sciences	1,864	7.53	1.96
	Surgery	2,563	3.14	0.78
	Tropical Medicine	381	1.88	0.31
	Urology & Nephrology	2,974	4.32	0.99
Communication & Textual Studies	Communication & Media Studies	277	2.60	0.82
	Languages & Linguistics	966	4.86	1.51
	Literary Studies	1,443	6.70	2.39
Earth & Environmental Sciences	Environmental Sciences	3,729	4.81	1.13
	Geochemistry & Geophysics	4,130	5.42	1.09
	Geology	1,681	10.45	2.37
	Meteorology & Atmospheric Sciences	5,301	6.15	1.25
	Oceanography	947	5.69	1.21
Economics & Business	Accounting	348	7.01	1.71
	Agricultural Economics & Policy	397	5.43	1.27
	Business & Management	2,613	4.51	1.12
	Development Studies	408	4.70	1.32
	Econometrics	264	7.57	1.66
	Economic Theory	256	5.54	1.22
	Economics	2,338	4.06	1.06
	Finance	839	5.35	1.25
	Industrial Relations	267	7.10	2.01
	Logistics & Transportation	1,065	4.26	1.14
	Marketing	815	5.12	1.18
	Sport, Leisure & Tourism	551	7.88	2.12
Enabling & Strategic Technologies	Bioinformatics	1,817	4.84	1.12
	Biotechnology	1,884	2.69	0.64
	Energy	9,382	3.72	0.99
	Materials	5,014	1.86	0.46
	Nanoscience & Nanotechnology	1,950	2.88	0.71
	Optoelectronics & Photonics	5,057	3.01	0.77
	Strategic, Defence, & Security Studies	1,792	4.14	1.11

	QUALITY/IMPACT				TRENDS		
	ARC score (2005–2010)	ARC rank (2005–2010)	International survey rank	% of Canadian survey respondents rating sub-field as strong	Change in share of world pubs. (%)	Change in ARC	Change in SI
	1.62	4	2	74	0.17	0.08	-0.06
	1.35	8	1	36	0.08	-0.07	-0.19
	1.49	3	15	45	0.40	0.20	0.02
	1.14	–	6	7	0.51	-0.07	0.05
	1.67	3	2	36	1.48	0.13	0.25
	0.80	9	3	57	0.41	-0.06	0.16
	1.13	7	4	46	-0.65	-0.14	-0.27
	1.02	6	1	52	0.29	0.36	0.01
	1.53	4	4	67	-0.60	-0.08	-0.23
	1.21	10	7	68	0.41	-0.15	0.03
	0.99	14	4	71	-1.11	-0.12	-0.63
	1.30	10	6	61	1.01	0.14	0.13
	1.23	10	7	57	1.11	-0.13	0.13
	0.81	8	4	52	1.96	-0.14	0.46
	0.97	11	1	59	-1.81	0.26	-0.69
	1.38	1	3	63	-0.57	0.06	-0.19
	0.67	14	3	50	0.29	-0.11	0.08
	0.73	9	4	57	1.31	-0.27	0.24
	1.19	4	7	44	0.18	0.39	0.01
	0.96	11	3	64	-0.57	0.00	-0.20
	0.88	6	4	76	1.36	-0.18	0.30
	0.80	8	–	55	-0.87	0.07	-0.46
	1.55	3	1	60	-0.65	0.13	-0.18
	1.13	9	4	38	0.72	0.05	0.07
	1.05	8	–	32	-0.61	0.09	-0.13
	0.94	13	5	40	0.45	0.05	0.10
	1.48	7	9	53	-0.13	0.13	-0.08
	1.44	7	4	66	0.35	-0.12	0.09
	1.53	5	9	59	-0.01	0.09	-0.01
	1.11	9	11	61	0.81	0.01	0.20
	1.45	4	11	67	0.51	0.03	0.10
	0.86	16	–	15	-0.61	-0.23	-0.17

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Field	Sub-Field	MAGNITUDE/INTENSITY # of papers (2005–2010)	Share of world pubs. (2005–2010) (%)	SI (2005–2010)
Engineering	Aerospace & Aeronautics	1,726	2.68	0.67
	Automobile Design & Engineering	942	8.37	2.30
	Biomedical Engineering	2,879	4.62	1.18
	Chemical Engineering	3,036	3.42	0.90
	Civil Engineering	2,950	5.07	1.41
	Electrical & Electronic Engineering	4,963	3.84	0.98
	Environmental Engineering	3,537	6.59	1.69
	Geological & Geomatics Engineering	2,748	5.69	1.48
	Industrial Engineering & Automation	4,748	3.07	0.79
	Mechanical Engineering & Transports	3,590	2.60	0.67
	Mining & Metallurgy	1,428	3.95	1.07
	Operations Research	2,380	5.06	1.15
Historical Studies	Anthropology	562	4.72	1.30
	Archaeology	441	4.24	1.03
	Classics	156	4.56	1.57
	History	714	4.15	1.49
	History of Science, Technology & Medicine	170	4.95	1.55
	History of Social Sciences	157	4.85	1.53
	Paleontology	1,312	5.43	1.08
Information & Communication Technologies	Artificial Intelligence & Image Processing	13,320	3.27	0.83
	Computation Theory & Mathematics	3,188	7.03	1.58
	Computer Hardware & Architecture	1,055	4.15	1.09
	Distributed Computing	754	4.11	1.09
	Information Systems	1,892	4.76	1.16
	Medical Informatics	1,193	8.06	2.21
	Networking & Telecommunications	16,205	4.91	1.31
	Software Engineering	2,922	5.89	1.57
Mathematics & Statistics	Applied Mathematics	1,157	2.78	0.61
	General Mathematics	4,166	4.06	0.88
	Numerical & Computational Mathematics	1,306	3.55	0.77
	Statistics & Probability	2,322	7.06	1.55

	QUALITY/IMPACT				TRENDS		
	ARC score (2005–2010)	ARC rank (2005–2010)	International survey rank	% of Canadian survey respondents rating sub-field as strong	Change in share of world pubs. (%)	Change in ARC	Change in SI
	1.33	10	7	73	-0.01	0.13	-0.02
	1.49	3	9	40	3.59	0.43	0.97
	1.13	9	6	67	0.30	0.01	0.06
	1.35	9	5	64	-0.77	0.23	-0.18
	1.19	11	4	63	-3.29	0.33	-0.95
	1.36	5	6	63	-0.31	0.18	-0.14
	1.17	11	6	65	0.30	-0.09	0.01
	1.38	8	3	79	-1.36	0.14	-0.44
	1.68	3	7	35	-0.51	0.40	-0.15
	1.29	13	7	54	-0.25	0.06	-0.11
	1.84	5	6	78	-0.51	-0.19	-0.21
	1.28	7	2	38	-0.58	0.11	-0.16
	1.24	6	5	44	1.17	-0.05	0.35
	1.22	6	5	47	-0.43	-0.10	-0.18
	1.74	1	7	30	0.92	0.60	0.25
	0.99	7	6	50	0.77	-0.16	0.16
	1.15	4	4	55	-1.83	0.01	-0.57
	1.37	2	4	39	0.06	0.16	0.13
	1.43	7	4	58	0.23	-0.16	-0.11
	1.27	7	5	57	-0.78	-0.15	-0.20
	1.17	8	3	57	-0.11	0.13	0.05
	1.28	4	5	35	0.00	0.29	0.01
	0.81	15	2	31	0.32	-0.36	0.17
	1.38	3	3	52	0.60	-0.12	0.10
	1.33	2	4	50	2.21	0.03	0.65
	1.38	4	6	81	-0.90	0.36	-0.30
	1.24	8	5	59	0.79	0.05	0.22
	0.96	11	6	67	-0.06	-0.11	-0.05
	1.19	5	9	71	0.27	0.03	0.04
	0.98	10	8	65	-0.65	-0.15	-0.15
	1.10	8	3	71	0.58	0.15	0.09

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Field	Sub-Field	MAGNITUDE/INTENSITY # of papers (2005–2010)	Share of world pubs. (2005–2010) (%)	SI (2005–2010)
Philosophy & Theology	Applied Ethics	748	7.00	2.15
	Philosophy	715	5.17	1.73
	Religions & Theology	561	5.73	2.01
Physics & Astronomy	Acoustics	2,108	5.51	1.46
	Applied Physics	5,303	1.71	0.39
	Astronomy & Astrophysics	4,218	5.76	0.74
	Chemical Physics	3,384	3.24	0.76
	Fluids & Plasmas	3,840	3.11	0.63
	General Physics	4,228	2.77	0.49
	Mathematical Physics	914	4.40	0.94
	Nuclear & Particles Physics	4,753	3.72	0.61
	Optics	2,142	3.18	0.79
Psychology & Cognitive Sciences	Behavioral Science & Comparative Psychology	1,477	8.29	2.07
	Clinical Psychology	1,484	7.55	1.94
	Developmental & Child Psychology	1,765	7.59	2.04
	Experimental Psychology	3,738	8.78	2.13
	General Psychology & Cognitive Sciences	157	3.37	0.96
	Human Factors	1,195	7.73	2.06
	Psychoanalysis	120	1.96	0.68
	Social Psychology	2,383	7.52	1.93
Public Health & Health Services	Epidemiology	1,319	6.97	1.47
	Gerontology	1,097	7.59	2.08
	Health Policy & Services	1,745	8.15	1.97
	Nursing	2,737	6.00	1.79
	Public Health	4,289	6.84	1.77
	Rehabilitation	2,391	8.34	2.33
	Speech-Language Pathology & Audiology	712	5.35	1.39
	Substance Abuse	1,008	5.90	1.52

	QUALITY/IMPACT				TRENDS		
	ARC score (2005–2010)	ARC rank (2005–2010)	International survey rank	% of Canadian survey respondents rating sub-field as strong	Change in share of world pubs. (%)	Change in ARC	Change in SI
	1.25	7	3	60	1.23	0.16	0.46
	0.73	10	3	63	0.58	-0.08	0.13
	0.86	5	6	47	0.37	0.15	0.00
	1.01	10	9	10	0.82	0.05	0.19
	1.11	10	10	42	0.10	0.02	0.02
	1.86	1	7	78	1.65	0.23	0.14
	1.17	8	8	35	0.00	0.06	0.01
	1.11	10	9	27	0.33	-0.03	0.05
	1.89	3	10	28	0.34	0.32	0.05
	0.94	8	7	52	0.27	-0.12	0.06
	1.76	1	8	59	0.44	0.36	0.05
	1.33	6	7	65	0.86	0.12	0.24
	1.02	12	4	61	0.86	-0.04	0.12
	1.19	4	3	79	1.21	-0.15	0.22
	1.27	8	3	85	1.67	0.02	0.36
	1.02	8	3	70	-0.32	0.05	-0.23
	0.90	2	4	75	-0.16	-0.02	-0.03
	1.22	7	4	33	2.03	0.09	0.41
	0.94	7	1	4	0.19	0.30	0.13
	1.20	6	5	62	-0.15	0.12	-0.15
	1.18	7	3	60	1.48	-0.01	0.14
	0.95	18	6	52	-0.22	0.05	-0.19
	1.22	4	3	71	1.90	-0.19	0.38
	1.55	6	3	51	-0.34	0.22	0.00
	1.12	7	3	64	0.59	0.19	0.07
	1.36	5	3	55	1.65	-0.08	0.46
	1.39	3	1	24	0.58	0.18	0.24
	0.96	7	1	54	1.46	-0.04	0.40

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Field	Sub-Field	MAGNITUDE/INTENSITY		
		# of papers (2005–2010)	Share of world pubs. (2005–2010) (%)	SI (2005–2010)
Social Sciences	Criminology	1,085	7.30	2.17
	Cultural Studies	359	3.94	1.33
	Demography	128	3.58	1.06
	Education	3,672	4.27	1.26
	Family Studies	246	4.77	1.37
	Gender Studies	287	7.04	2.19
	Geography	1,609	6.84	1.95
	Information & Library Sciences	950	4.21	1.32
	International Relations	504	4.69	1.71
	Law	347	1.80	0.73
	Political Science & Public Administration	1,173	4.20	1.34
	Science Studies	427	4.99	1.42
	Social Sciences Methods	303	6.40	1.76
	Social Work	554	5.88	1.71
	Sociology	711	5.15	1.60
Visual & Performing Arts	Art Practice, History, & Theory	72	2.62	0.98
	Drama & Theater	76	5.92	2.41
	Folklore	7	0.87	0.48
	Music	131	4.57	1.49

	QUALITY/IMPACT				TRENDS		
	ARC score (2005–2010)	ARC rank (2005–2010)	International survey rank	% of Canadian survey respondents rating sub-field as strong	Change in share of world pubs. (%)	Change in ARC	Change in SI
	1.37	1	3	62	-0.35	-0.02	-0.29
	0.80	10	3	62	-0.43	-0.28	-0.14
	0.65	7	4	51	-0.31	-0.30	0.05
	1.21	9	4	60	0.35	-0.12	0.05
	0.63	5	–	44	0.04	-0.13	-0.02
	0.91	5	1	57	0.70	-0.15	0.16
	1.25	8	4	67	1.24	-0.10	0.39
	1.17	9	3	50	-0.21	0.01	-0.04
	1.37	4	4	44	-0.16	0.41	0.12
	1.01	7	3	57	0.05	-0.18	0.04
	0.85	14	5	61	-0.39	0.05	-0.15
	0.89	13	9	46	0.24	0.19	0.02
	0.81	7	6	44	1.27	-0.31	0.50
	1.03	5	1	49	1.50	-0.01	0.49
	0.75	9	5	35	1.20	-0.03	0.38
	–	–	11	56	0.63	–	0.23
	–	–	6	70	2.27	–	0.39
	–	–	–	50	-1.97	–	-1.44
	–	–	1	60	1.69	–	0.50

Note: Numbers in red are based on less than 30 observations. SI = Specialization Index; ARC = average relative citations; ARC rank = Canada's rank by ARC for 2005–2010 — See Chapter 4 for full definitions of these indicators). Other variables are drawn from the survey of top-cited researchers worldwide and the survey of Canadian S&T experts (see Chapter 5). "Trends" are for the period 2005–2010 compared with 1999–2004.

11

Conclusions

- The State of S&T in Canada
- Areas of S&T Strength
- Regional S&T Strengths
- Improving and Declining Areas of S&T
- Emerging Areas
- The Way Forward

11 Conclusions

The purpose of this final chapter is to answer the main question and the two sub-questions that comprise the charge to the Panel. The answers provided are based on the evidence and analyses presented in Chapters 4 through 10, and, in the Panel's judgment, represent the most accurate responses that the assessment instruments and data will permit.

11.1 THE STATE OF S&T IN CANADA

What is the current state of science and technology in Canada?

The preponderance of evidence indicates that Canadian S&T, within the scope of this assessment, is healthy and growing in both output and impact. With less than 0.5 per cent of the world's population, Canada produces 4.1 per cent of the world's scientific papers — seventh in the world — and nearly 5 per cent of the world's most frequently cited papers — sixth in the world. In 2005–2010, Canada produced 59 per cent more papers than in 1999–2004, the only G7 country with an increase above the world average of 54 per cent.

Also impressive has been the overall impact of Canadian S&T, as measured by the Average Relative Citations (ARC) index, which increased from 1.27 to 1.36 during the same timeframe. Canada's overall ARC score ranks it sixth highest in the world; and on a field-by-field basis, Canada's ARC rankings place it among the 5 leading countries in the world in 7 of 22 fields of research, and among the 10 leading countries in a further 14 fields.

These bibliometric measurements undoubtedly contribute to the high international regard for the quality and rigour of Canada's S&T. Among surveyed authors of the world's top-cited scientific papers, 37 per cent identified Canada as one of the five leading countries in their field, placing Canada fourth overall in the world, behind only the United States, the United Kingdom, and Germany. Sixty-eight per cent rated Canadian research in their field as being strong compared with the rest of the world. Many of these top-cited researchers also identified a number of world-leading major research facilities and programs in Canada. Canadian S&T experts considered Canada's S&T enterprise to be strong, although half of those surveyed thought Canada had lost ground in the past five years.

Canada is part of a network of international S&T collaboration that includes the most scientifically advanced countries in the world. Canada is ninth in the world in production of doctoral graduates, and Canadian S&T attracts high-quality researchers from abroad, such that over the past decade there has been a net migration of researchers into the country. The overall impact of international circulation of highly qualified and skilled personnel on the quality of Canadian research has been neutral, based on the ARC scores of researchers entering and leaving the country.

In contrast to the nation's strong performance in knowledge generation is its weaker performance in quantity of patents. However, Canada excels in international comparisons of quality, with citations to patents (ARC scores) ranking second in the world, behind the United States. An analysis of the factors underlying the long-standing discrepancy between knowledge generation and technology development in Canada is beyond the mandate of this assessment, but has been the subject of several recent studies (see CCA, 2009; STIC, 2011; Industry Canada, 2011b).

11.2 AREAS OF S&T STRENGTH

Considering both basic and applied research fields, what are the scientific disciplines and technological applications in which Canada excels? How do these trends compare with what has been taking place in comparable countries?

As illustrated throughout this report, each method of evaluating S&T has its advantages and limitations; no single measurement alone can fully evaluate S&T across all fields. Chapter 10 provided a multi-lens synthesis of findings to describe each research field and to identify world-leading sub-fields.

Since no single measure alone can be used to identify excellence, depending on the weighting given to each lens, different fields will emerge among the strongest. The Panel determined two measures of quality, the field's international ARC rank and its rank in the international survey, to be the most relevant in determining the field's position compared with other advanced countries. Based on these measures of quality, the Panel identified six research fields in which Canada excels. These fields are (in alphabetical order):

- Clinical Medicine[42]
- Historical Studies
- Information and Communication Technologies (ICT)
- Physics and Astronomy
- Psychology and Cognitive Sciences
- Visual and Performing Arts

42 As noted previously (Section 2.1), the scope of some research fields as defined in this assessment (particularly Clinical Medicine and Historical Studies) is broader than the scope commonly used by academic disciplines, institutional departments, and funding agencies.

When evaluated on the basis of citation indices (ARC scores), Canada places among the top five countries in the world in five of these fields. In five fields, Canada is also ranked among the top five countries in the world by leading international researchers (see Figure 11.1). Three of the fields (Clinical Medicine, ICT, Physics and Astronomy) are also among the five largest research enterprises in the country in terms of output of scientific papers; and one of the fields, ICT, accounts for 44 per cent of Canada's patents. Notwithstanding the challenge of assessing research strength in the humanities, social sciences, and creative arts (see Section 2.4), three of the fields (Historical Studies, Psychology and Cognitive Sciences, Visual and Performing Arts) are at least partly, if not completely, in these disciplines. Collectively, these six fields of strength attest to the breadth of Canadian research excellence.

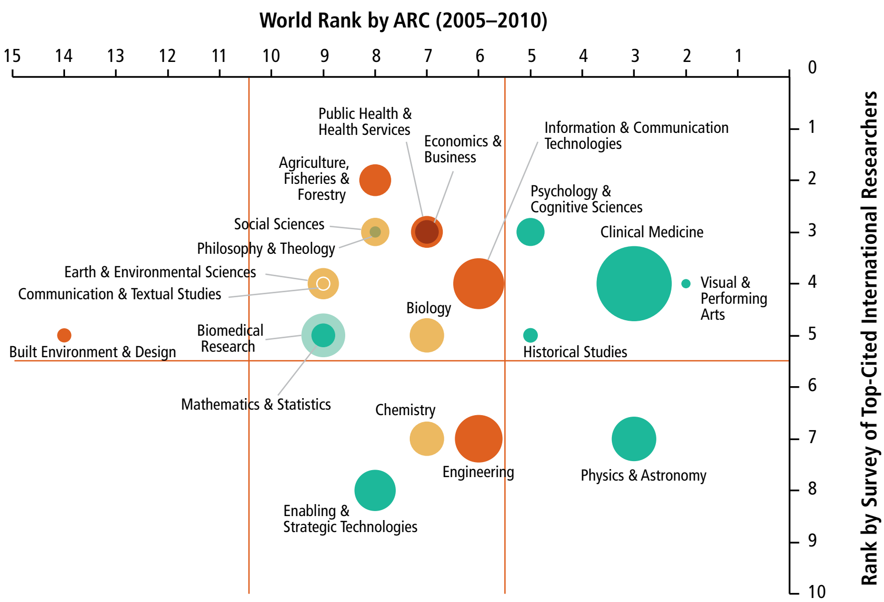

Figure 11.1

International Survey Rank versus ARC Rank

This figure shows Canada's rank in each field by Average Relative Citations (ARC) in the period 2005–2010 on the x-axis, and ranking in terms of the reputation of Canadian research in the survey of top-cited international researchers on the y-axis. The size of the bubble is proportional to the number of papers produced in 2005–2010. Bubbles are coloured according to whether Canada's share of world papers in that field increased (green), decreased (red), or remained approximately the same (yellow — defined as an increase or decrease of less than 0.2 per cent) compared with the period 1999-2004. ARC rank is out of the top 19 countries by total papers produced in that field of research.

Much of the nuance of Canadian strength is at the sub-field level. Sub-field strengths are identified for each field in Chapter 10. In nine sub-fields (with their respective fields in parentheses) Canada leads the world in scientific impact, as measured by bibliometrics (ARC rank):

- Anatomy and Morphology (Biomedical Research)
- Astronomy and Astrophysics (Physics and Astronomy)
- Business and Management (Economics and Business)
- Classics (Historical Studies)
- Criminology (Social Sciences)
- Dermatology and Venereal Diseases (Clinical Medicine)
- General and Internal Medicine (Clinical Medicine)
- Nuclear and Particles Physics (Physics and Astronomy)
- Zoology (Biology)

Of these sub-fields, four (Anatomy and Morphology, Business and Management, Criminology, Zoology) are based in fields other than the six fields of strength identified above.

The data related to strengths in technological applications are less comprehensive, but it is of note that Canadian patents related to ICT, Chemicals, and AgriFood have a greater impact than the world average.

11.3 REGIONAL S&T STRENGTHS

How are these strengths distributed geographically across the country?

Collectively, Ontario, Quebec, British Columbia, and Alberta are the powerhouse of Canadian S&T, accounting for 97 per cent of total Canadian output in terms of scientific papers, compared with having 86 per cent of the national population. Ontario produces 46 per cent of Canada's bibliometric output, in keeping with the 45 per cent of Canada's gross domestic expenditure on research and development (GERD) that is spent in Ontario. British Columbia is the leading province in terms of impact as measured by ARC indices.

The geographic distribution of the six fields of strength is difficult to determine with precision because of the diminished reliability of data below the national level, and the vastly different size of the research enterprise in each province. The most reliable data that are independent of size are provincial ARC scores. Using this metric, the leading provinces in each field are as follows:

- Clinical Medicine: Ontario, Quebec, British Columbia, Alberta
- Historical Studies: New Brunswick, Ontario, British Columbia
- ICT: British Columbia, Ontario
- Physics and Astronomy: British Columbia, Alberta, Ontario, Quebec
- Psychology and Cognitive Sciences: British Columbia, Nova Scotia, Ontario
- Visual and Performing Arts: Quebec

11.4 IMPROVING AND DECLINING AREAS OF S&T

In which scientific disciplines and technological applications has Canada shown the greatest improvement/decline in the last five years? What major trends have emerged?

In comparing results with the 2006 S&T report, some apparent changes may be related, at least in part, to the differences in bibliometric databases and classification between the two assessments. Therefore, the impact of these differences was mitigated by mapping the four areas of strength identified in the 2006 report (natural resources, health and related life sciences and technologies, information and communication technologies, and environmental S&T) to the classification system used in the current report. The trends in these areas are exemplified by ARC scores, which are presented in Table 11.1 for illustrative purposes. For two areas noted as strengths in 2006, health and ICT, the impact of research has continued to increase. Indeed these two areas, represented in part in 2012 by Clinical Medicine and ICT, continue to be among the Canadian strengths identified in Section 11.2. However, the other two areas identified as strengths in 2006, natural resources and environmental S&T, have declined since 2006, not only in ARC scores, but also in share of world publications and in a growing proportion of Canadian S&T experts identifying the fields as falling behind.

Table 11.1
Average Relative Citations for Research in Four Areas of Strength Identified in 2006 State of S&T Report

2006 areas of strength	Corresponding fields (bold) and sub-fields in the current classification	ARC 2005–2010	ARC 1999–2004
Natural Resources	**Agriculture, Fisheries & Forestry**	1.25	1.25
	Mining & Metallurgy	1.84	2.03
	Energy	1.44	1.56
	Geochemistry & Geophysics	1.21	1.36
	Geology	0.99	1.11
	Geological & Geomatics Engineering	1.38	1.52
Health and Related Life S&T	**Biomedical Research**	1.18	1.11
	Clinical Medicine	1.59	1.49
	Public Health & Health Services	1.24	1.17
ICT	**Information & Communication Technologies**	1.30	1.17
Environmental S&T	Environmental Sciences	1.53	1.61
	Environmental Engineering	1.17	1.26
	Biology	1.34	1.18

Note: Bolded text refers to fields (which include their sub-fields) (e.g., the sub-field Fisheries is included in the field Agriculture, Fisheries, and Forestry). To view all sub-field data see Table 10.2.

That natural resources and environmental S&T are not identified as areas of strength in this report does not imply that they are areas of weakness. In fact these areas exhibit particular strengths in terms of international reputation (Agriculture, Fisheries, and Forestry was ranked second in the world by top-cited international researchers, the highest of any field) and publication volume. There is also considerable variation within each area. For example, within environmental S&T, although Environmental Sciences and Environmental Engineering have declined, the field of Biology has improved considerably. The declines that are seen are relative to the world: Canada is making gains in these areas, but not as fast as the world average. Nearly all advanced countries have S&T priorities related to natural resources and environment (see Appendix 9), and this intense global competition likely underlies these relative declines.

Apart from the fields of Clinical Medicine, ICT, and Biology (discussed above), the Panel has also concluded that real improvements have occurred in Physics and Astronomy, Psychology and Cognitive Sciences, Public Health and Health Services, and Visual and Performing Arts.

11.5 EMERGING AREAS

Which scientific disciplines and technological applications have the potential to emerge as areas of prominent strength for Canada?

Although robust methods of identifying emerging areas of S&T are still in their infancy, the Panel used new bibliometric techniques to identify research clusters and their rates of growth. Rapidly emerging research clusters in Canada have keywords relating, most notably, to:

- wireless technologies and networking,
- information processing and computation,
- nanotechnologies and carbon nanotubes, and
- digital media technologies.

The Survey of Canadian S&T Experts pointed to personalized medicine and health care, several energy technologies, tissue engineering, and digital media as areas in which Canada is well placed to become a global leader in development and application.

11.6 THE WAY FORWARD

This report provides an overview of the state of S&T in Canada using a multi-lens approach. The conclusions reached by the Panel are based on its interpretation of the evidence provided in Chapters 4 through 9. The Panel also makes the following observations:

- The conclusions reached in this report are based on the best available evidence, but given the wealth of data, additional analysis is possible, particularly at the sub-field level. Readers are therefore encouraged to consult the data provided in the report and in the appendices (available online) for deeper insights into specific areas.
- The Panel hopes that the report will spur further discussion in the humanities, arts, and social sciences on how these fields should be assessed on a macro scale, and how the data required for such assessments could be collected. The Panel made a determined effort to analyze the output and impact of books,

book chapters, exhibitions, presentations, and other outputs in these fields, but was not successful because of the lack of comprehensive data both in Canada and internationally. With today's computing power, the development of such databases should be feasible.

- The Panel has noted the many changes that have occurred in the Canadian S&T enterprise since the first Council report in 2006. The current report is another snapshot in time of a dynamic, rapidly evolving, and highly competitive environment. Therefore, assessing S&T in Canada is a constant work in progress, which the Council has been privileged to study on two occasions. It looks forward to the possibility of doing so again in another five years aided by further technological and methodological advances.

Box 11.1
Issues for Further Study of the State of S&T in Canada

There are many possible avenues for further study of S&T. For example:

- In light of the limitations of field-based bibliometrics, newer methods, such as the cluster analysis used in Chapter 6 of this report, hold considerable promise for the future. Although currently in their infancy, in time these techniques may be better able to reflect the true organization of S&T without the constraints of imposed top-down classification systems.
- The absence of bibliometric databases for books, equivalent to those for journal publications, is a significant gap in fully assessing S&T output and impact.
- It was beyond the mandate of this Panel, but bibliometric analysis could likely be used to address the question of whether the creation of formal networks, institutes, or consortia increases S&T output and impact.
- Patent data are an incomplete measure of the applied research output of the higher education sector. Internationally comparable measures of applied research are a current gap in knowledge in this area.
- Further study could determine whether the attractiveness of specific doctoral programs to international students is related to S&T output and impact of the program, or primarily to other factors.

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Assessments of the Council of Canadian Academies

The assessment reports listed below are accessible through the Council's website (www.scienceadvice.ca):

- The State of Science and Technology in Canada (2012)
- Informing Research Choices: Indicators and Judgment (2012)
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- Small is Different: A Science Perspective on the Regulatory Challenges of the Nanoscale (2008)
- Influenza and the Role of Personal Protective Respiratory Equipment: An Assessment of the Evidence (2007)
- The State of Science and Technology in Canada (2006)

The assessments listed below are in the process of expert panel deliberation:

- Canadian Ocean Science
- Energy Prices – Impacts and Adaptation: Assessing Canada's Preparedness
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