Competing in a Global Innovation Economy: The Current State of R&D in Canada

Expert Panel on the State of Science and Technology and Industrial Research and Development in Canada

Council of Canadian Academies
Conseil des académies canadiennes

Science Advice in the Public Interest

COMPETING IN A GLOBAL INNOVATION ECONOMY: THE CURRENT STATE OF R&D IN CANADA

Expert Panel on the State of Science and Technology and Industrial Research and Development in Canada

THE COUNCIL OF CANADIAN ACADEMIES
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This report was prepared for the Government of Canada in response to a request from the Minister of Science. Any opinions, findings, or conclusions expressed in this publication are those of the authors, the Expert Panel on the State of Science and Technology and Industrial Research and Development in Canada, and do not necessarily represent the views of their organizations of affiliation or employment, or the sponsoring organization, Innovation, Science and Economic Development Canada.

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All CCA assessments undergo a formal report review and are published and made available to the public free of charge. Assessments can be referred to the CCA by foundations, non-governmental organizations, the private sector, or any level of government.

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Founded in 1882, the RSC comprises the Academies of Arts, Humanities and Sciences, as well as Canada's first national system of multidisciplinary recognition for the emerging generation of Canadian intellectual leadership: The College of New Scholars, Artists and Scientists. Its mission is to recognize scholarly, research, and artistic excellence, to advise governments and organizations, and to promote a culture of knowledge and innovation in Canada and with other national academies around the world.

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Expert Panel on the State of Science and Technology and Industrial Research and Development in Canada

Under the guidance of its Scientific Advisory Committee, Board of Directors, and Member Academies, the CCA assembled the Expert Panel on the State of Science and Technology and Industrial Research and Development in Canada to undertake this project. Each expert was selected for his or her expertise, experience, and demonstrated leadership in fields relevant to this project.

Max Blouw (Chair), Former President and Vice-Chancellor of Wilfrid Laurier University (Waterloo, ON)

Luis Barreto, President, Dr. Luis Barreto & Associates and Strategic Advisor, NEOMED-LABS (Concord, ON)

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David A. Wolfe, Professor, Political Science and Co-Director, Innovation Policy Lab, Munk School of Global Affairs, University of Toronto (Toronto, ON)

Message from the Chair

Canada's aspiration to increase national prosperity by becoming a more innovative country is long-standing, but hardly unique. Embedded in a rapidly-evolving global economy, Canada competes intensely in an international race to foster the next wave of research advances and innovations. A recent decline in Canada's ranking on the 2018 Bloomberg Innovation Index is the most recent evidence of the intensity of this competition, and of Canada's faltering place in it. With deep pools of research talent and considerable R&D assets, it is my view that Canada can be among the leaders in this race. Achieving a lead position will require concerted and sustained actions that build upon a careful assessment of the underpinnings of innovation and wealth creation in Canada.

This Expert Panel was tasked to assess evidence on the foundations of innovation, including Canada's recent track record in: fundamental research, applied research and development, business-led R&D, and the relationship of these research efforts to wealth creation and prosperity through innovation. To be clear, innovation does not require research. There are many innovative firms and individuals without formal research programs. However, countries are increasingly ramping up their investments in R&D because it is through R&D that new ideas are reliably and purposefully developed. More important, it is also through R&D that talented people are trained, enhancing their skills in inquiry and problem solving so they can advance the margins of what we know and what we are capable of creating. Unleashing the potential of highly-skilled people to generate and develop new ideas into products, processes, organizations, and systems is the most important function of R&D, and the key to creating lasting prosperity.

Some of the data the Panel reviewed were encouraging. Canada benefits from high levels of educational attainment, and has significant areas of research strength. However, other countries are accelerating their R&D efforts, and the Panel found the trajectory of many aspects of Canadian R&D worrying. Dwindling financial support for R&D across all sectors, most notably in the business sector, is of particular concern. The increasing flow of intellectual property out of Canada is also alarming. More patents are now invented in Canada than are owned in Canada. As a small, open economy, Canada is often an attractive place for companies to conduct R&D (or to procure its products such as patents and talented innovators). However, it is too often a less attractive place for developing and commercializing products, and growing companies with global reach. The end result is a loss of economic benefits and opportunities for Canada.

In summary, while Canada's performance in R&D has retained momentum gained from prior investments, its future is now jeopardized by both relatively low levels of R&D and by the propensity of successful Canadian innovations, entrepreneurs, and researchers to leave the country to pursue opportunities for commercialization and growth elsewhere. Canada's capacity for R&D and innovation remains excellent, but the underpinnings of that capacity are eroding and we are less successful in creating domestic wealth from its innovations than many other jurisdictions.

It was a genuine pleasure to work with the members of this Panel, and I sincerely thank them for their passionate engagement with our charge, their energy, and their good humor as we debated the meaning and causal drivers behind the evidence we were examining. I also appreciated their unflagging willingness to step back from topics of particular personal enthusiasm to reflect on the wider work of the group.

It was also a marvelous experience to work with the exceptional, talented staff of the CCA. They (mostly) did not complain when asked to assemble more evidence, or reanalyze evidence through a different lens, or add endless new requests for sometimes impossible-to-find (but wouldn't it be wonderful if we could) new evidence. The CCA staff is a remarkable collection of individuals doing very important work for our country, and I am in their debt.

I view this assessment as a contribution to critically important discussions on R&D and innovation in Canada, and I look forward to continuing to follow those conversations — and participate in them — as they evolve.

Sincerely,

Max Blouw, Chair,
Expert Panel on the State of Science and Technology and
Industrial Research and Development in Canada

Message from the President and CEO

This assessment of Canada's performance indicators in science, technology, research, and innovation comes at an opportune time. The Government of Canada has expressed a renewed commitment in several tangible ways to this broad domain of activity including its *Innovation and Skills Plan*, the announcement of five superclusters, its appointment of a new Chief Science Advisor, and its request for the *Fundamental Science Review*. More specifically, the 2018 Federal Budget demonstrated the government's strong commitment to research and innovation with historic investments in science.

The CCA has a decade-long history of conducting evidence-based assessments about Canada's research and development activities, producing seven assessments of relevance:

- *The State of Science and Technology in Canada* (2006)
- *Innovation and Business Strategy: Why Canada Falls Short* (2009)
- *Catalyzing Canada's Digital Economy* (2010)
- *Informing Research Choices: Indicators and Judgment* (2012)
- *The State of Science and Technology in Canada* (2012)
- *The State of Industrial R&D in Canada* (2013)
- *Paradox Lost: Explaining Canada's Research Strength and Innovation Weakness* (2013)

Using similar methods and metrics to those in *The State of Science and Technology in Canada* (2012) and *The State of Industrial R&D in Canada* (2013), this assessment tells a similar and familiar story: Canada has much to be proud of, with world-class researchers in many domains of knowledge, but the rest of the world is not standing still. Our peers are also producing high quality results, and many countries are making significant commitments to supporting research and development that will position them to better leverage their strengths to compete globally. Canada will need to take notice as it determines how best to take action. This assessment provides valuable material for that conversation to occur, whether it takes place in the lab or the legislature, the bench or the boardroom. We also hope it will be used to inform public discussion.

It is also worth noting that the Panel itself recognized the limits that come from using traditional historic metrics. Additional approaches will be needed the next time this assessment is done.

I would like to thank Max Blouw, the Panel Chair, and his fellow expert panel members for their insightful work on this topic. I'd also like to thank the CCA's Board of Directors, its Scientific Advisory Committee, and its three

Member Academies — the Royal Society of Canada, the Canadian Academy of Engineering, and the Canadian Academy of Health Sciences — who continue to provide the wisdom, advice, and expert knowledge that helps keep the CCA pointed in the right direction.

Finally, I would like to thank the Minister of Science the Hon. Kirsty Duncan, and the Minister of Innovation, Science and Economic Development, the Hon. Navdeep Bains, for referring this topic to the CCA.

Eric M. Meslin, PhD, FCAHS
President and CEO, Council of Canadian Academies

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The Panel could not have done its job without assistance from many individuals and organizations, especially those that provided data, evidence, and analysis for our review. This includes all three members of the Tri-Agency (the Natural Sciences and Engineering Research Council, the Social Sciences and Humanities Research Council, and the Canadian Institutes for Health Research), the National Research Council of Canada, the Canada Foundation for Innovation, and the Federation of the Humanities and Social Sciences. It also includes Humber College, Colleges and Institutes Canada, Polytechnics Canada, TechAccess Canada, and Reseau TransTech, which together shared evidence and insights on the roles of colleges and polytechnics in Canada. With respect to our analysis of R&D expenditures, Louise Earl and her team at Statistics Canada were kind enough to repeatedly field questions about their data collection methodologies and greatly improved our understanding of this data. Our analysis also would not have been possible without the work of Science-Metrix, and EKOS Research, which respectively supplied the bibliometric and survey data used in this study. Finally, we are grateful to the 5,547 highly-cited researchers from all over the world who took the time to respond to our survey and help us better understand Canada's place in the global R&D and innovation landscape.

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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 (CCA) 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 CCA.

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

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Raymond G. Siemens, Distinguished Professor, English and Computer Science and Former Canada Research Chair in Humanities Computing, University of Victoria (Victoria, BC)

The report review procedure was monitored on behalf of the CCA's Board of Directors and Scientific Advisory Committee by **Gregory S. Kealey, C.M., FRSC,** Professor Emeritus, Department of History, University of New Brunswick. The role of the peer review monitor is to ensure that the Panel gives full and fair consideration to the submissions of the report reviewers. The Board of the CCA authorizes public release of an expert panel report only after the peer review monitor confirms that the CCA's report review requirements have been satisfied. The CCA thanks Dr. Kealey for his diligent contribution as peer review monitor.

Executive Summary

National prosperity, competitiveness, and well-being are inextricably linked to the capacity to participate in and benefit from research, development, and innovation. A confluence of advances in digital technologies, biotechnology, networked production processes, and autonomous transportation systems could usher in profound economic, social, environmental, and technological shifts in the years to come. Countries that strategically support research and experimental development (R&D) and innovation, and cultivate an extensive base of research talent and expertise, will benefit from coming research advances and discoveries. Countries that do not provide such support or cultivate such skills risk becoming unable to participate in world-leading research and equally unable to reap its eventual social and economic benefits. Policy-makers need a broad spectrum of information, indicators, and insights to support the strongest possible development of broad-based R&D capacity. This report assesses the latest evidence on Canada's R&D and innovation performance, combining up-to-date data with expert insights and analyses, and benchmarking against the performance of other countries.

Charge to the Panel

In 2016, the federal government asked the Council of Canadian Academies (CCA) to undertake a comprehensive assessment of the state of science, technology, and R&D in Canada. The CCA had completed assessments on this topic in 2006 and 2012. Both reports provided a snapshot in time of performance in all fields of research and technology development. A third report, on the state of industrial R&D and gaps in translating R&D strengths to innovation, was published in 2013. The current Expert Panel (the Panel) was tasked with considering the combined charges from the 2012 and 2013 assessments, consisting of the following questions:

> *What is the current state of science and technology and industrial research and development in Canada?*
>
> - *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, and why? Which scientific disciplines and technological applications have the potential to emerge as areas of prominent strength for Canada?*

- *What are the existing industrial R&D strengths in Canada? How are these strengths distributed by sector and 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 are our relative strengths most aligned with Canada's economic strengths/industry needs?*

- *What are the key barriers and knowledge gaps in translating Canadian strengths in S&T into innovation and wealth creation?*

On Terminology

Terms such as *science*, *research and development*, *technology*, and *innovation*, are often imprecisely and inconsistently applied. Past CCA assessments used the blanket term *science and technology* (S&T). This Panel opted to use the more inclusive term *research and experimental development* (R&D). *R&D* as used here refers to research activities spanning all fields of study, encompassing all stages of research and technology development and performed in all sectors, (i.e., academia, government, industry, and the not-for-profit sector). *Innovation* is not a central focus of the report; however, where relevant to its discussions, the Panel adopted a broad definition of innovation, recognizing that by convention it is often measured as the introduction of new products, processes, organizational methods, or marketing methods in firms. While efforts are underway to extend such measurements to the sphere of social or public-sector innovation, currently there are few internationally comparable data on innovation activities outside of firms. When analyzing internationally comparable data, the Panel relied on standard definitions of R&D and related terms (e.g., basic research, applied research), as defined by the Organisation for Economic Co-operation and Development (OECD) and statistical agencies. Some of these definitions have significant limitations, though they remain the only consistent way to benchmark Canadian performance against that of other nations.

Methodology and Data Limitations

The Panel relied on evidence from multiple sources to address its charge, including a literature review and data extracted from statistical agencies and organizations such as Statistics Canada and the OECD. For international comparisons, the Panel focused on OECD countries along with developing countries that are among the top 20 producers of peer-reviewed research publications (e.g., China, India, Brazil, Iran, Turkey). In addition to the literature review, two primary research approaches informed the Panel's assessment:

- a comprehensive bibliometric and technometric analysis of Canadian research publications and patents; and,
- a survey of top-cited researchers around the world.

Despite best efforts to collect and analyze up-to-date information, one of the Panel's findings is that data limitations continue to constrain the assessment of R&D activity and excellence in Canada. This is particularly the case with industrial R&D and in the social sciences, arts, and humanities. Data on industrial R&D activity continue to suffer from time lags for some measures, such as internationally comparable data on R&D intensity by sector and industry. These data also rely on industrial categories (i.e., NAICS and ISIC codes) that can obscure important trends, particularly in the services sector, though Statistics Canada's recent revisions to how this data is reported have improved this situation. There is also a lack of internationally comparable metrics relating to R&D outcomes and impacts, aside from those based on patents.

For the social sciences, arts, and humanities, metrics based on journal articles and other indexed publications provide an incomplete and uneven picture of research contributions. The expansion of bibliometric databases and methodological improvements such as greater use of web-based metrics, including paper views/downloads and social media references, will support ongoing, incremental improvements in the availability and accuracy of data. However, future assessments of R&D in Canada may benefit from more substantive integration of expert review, capable of factoring in different types of research outputs (e.g., non-indexed books) and impacts (e.g., contributions to communities or impacts on public policy). The Panel has no doubt that contributions from the humanities, arts, and social sciences are of equal importance to national prosperity. It is vital that such contributions are better measured and assessed.

R&D Investment and Capacity

Canada's international reputation for its capacity to participate in cutting-edge R&D is strong, with 60% of top-cited researchers surveyed internationally indicating that Canada hosts world-leading infrastructure or programs in their fields. This share increased by four percentage points between 2012 and

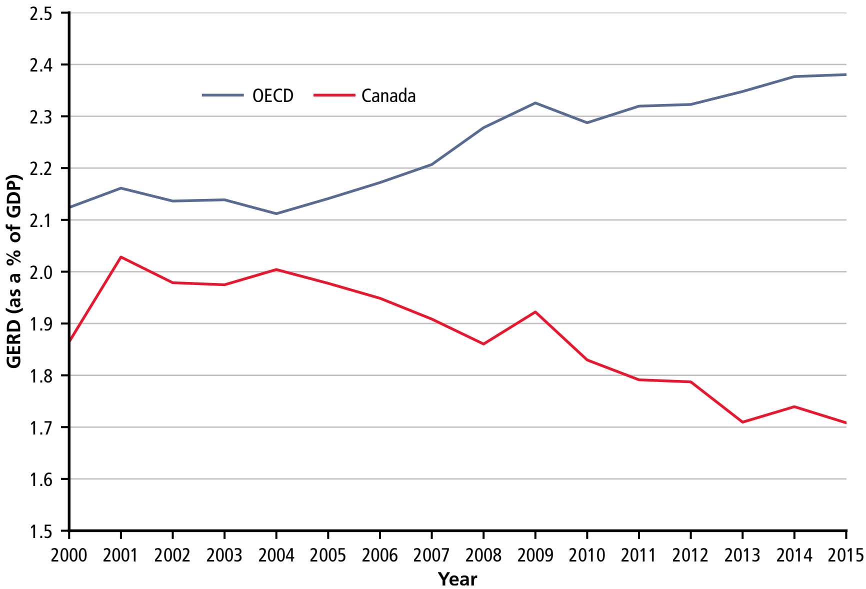
2017. Canada continues to benefit from a highly educated population and deep pools of research skills and talent. Its population has the highest level of educational attainment in the OECD in the proportion of the population with a post-secondary education. However, among younger cohorts (aged 25 to 34), Canada has fallen behind Japan and South Korea. The number of researchers per capita in Canada is on a par with that of other developed countries, and increased modestly between 2004 and 2012. Canada's output of PhD graduates has also grown in recent years, though it remains low in per capita terms relative to many OECD countries.

In contrast, the number of R&D personnel employed in Canadian businesses dropped by 20% between 2008 and 2013. This is likely related to sustained and ongoing decline in business R&D investment across the country. R&D as a share of gross domestic product (GDP) has steadily declined in Canada since 2001, and now stands well below the OECD average (Figure 1). As one of few OECD countries with virtually no growth in total national R&D expenditures between 2006 and 2015, Canada would now need to more than double expenditures to achieve an R&D intensity comparable to that of leading countries.

Low and declining business R&D expenditures are the dominant driver of this trend; however, R&D spending in all sectors is implicated. Government R&D expenditures declined, in real terms, over the same period. Expenditures in the higher education sector (an indicator on which Canada has traditionally ranked highly) are also increasing more slowly than the OECD average. Significant erosion of Canada's international competitiveness and capacity to participate in R&D and innovation is likely to occur if this decline and underinvestment continue.

Research Output, Impact, and Strength

Between 2009 and 2014, Canada produced 3.8% of the world's research publications, ranking ninth in the world. This is down from seventh place for the 2003–2008 period. India and Italy have overtaken Canada although the difference between Italy and Canada is small. Publication output in Canada grew by 26% between 2003 and 2014, a growth rate greater than many developed countries (including United States, France, Germany, United Kingdom, and Japan), but below the world average, which reflects the rapid growth in China and other emerging economies. Research output from the federal government, particularly the National Research Council Canada, dropped significantly between 2009 and 2014.



Data Source: OECD, 2016a

Figure 1

R&D Intensity in Canada and the OECD, 2000–2015

Canada's R&D intensity or Gross Domestic Expenditures on R&D (GERD) as a share of GDP has declined steadily since peaking in 2001. Across OECD countries, however, R&D spending relative to GDP has continued to increase. The OECD average is now 2.4% of GDP and leading countries have R&D intensities above 4%.

Canada, relative to the world, specializes in subjects generally referred to as the humanities and social sciences (plus health and the environment), and does not specialize as much as others in areas traditionally referred to as the physical sciences and engineering. Specifically, Canada has comparatively high levels of research output in Psychology and Cognitive Sciences, Public Health and Health Services, Philosophy and Theology, Earth and Environmental Sciences, and Visual and Performing Arts. It accounts for more than 5% of world research in these fields. Conversely, Canada has lower research output than expected in Chemistry, Physics and Astronomy, Enabling and Strategic Technologies, Engineering, and Mathematics and Statistics. The comparatively low research output in core areas of the natural sciences and engineering is concerning, and could impair the flexibility of Canada's research base, preventing research institutions and researchers from being able to pivot to tomorrow's emerging research areas.

Canada is maintaining its international standing in measures of research impact, though evidence suggests a minor erosion of competitiveness in some fields. Its Average Relative Citation (ARC) rank in 2009–2014 remained unchanged at sixth place from 2003 to 2008 (Figure 2). Canada's research reputation also remained unchanged at fourth place, according to a survey of top-cited researchers from around the world, with around 36% of respondents identifying Canada as among the top five countries in their field. The country's ARC scores are above the world average in all fields in 2009–2014. Canada ranks among the top five countries in Psychology and Cognitive Sciences, Clinical Medicine, Physics and Astronomy, Historical Studies, and Visual and Performing Arts.

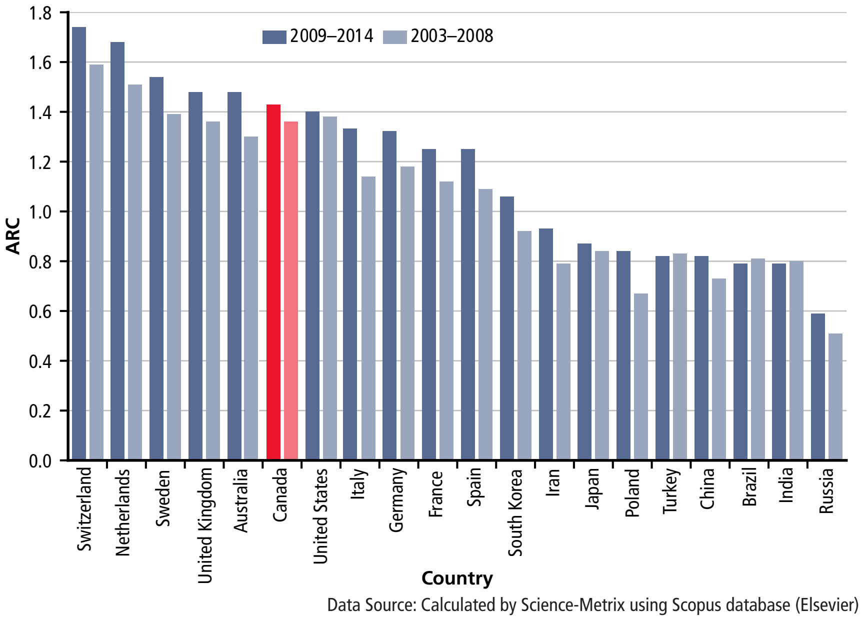


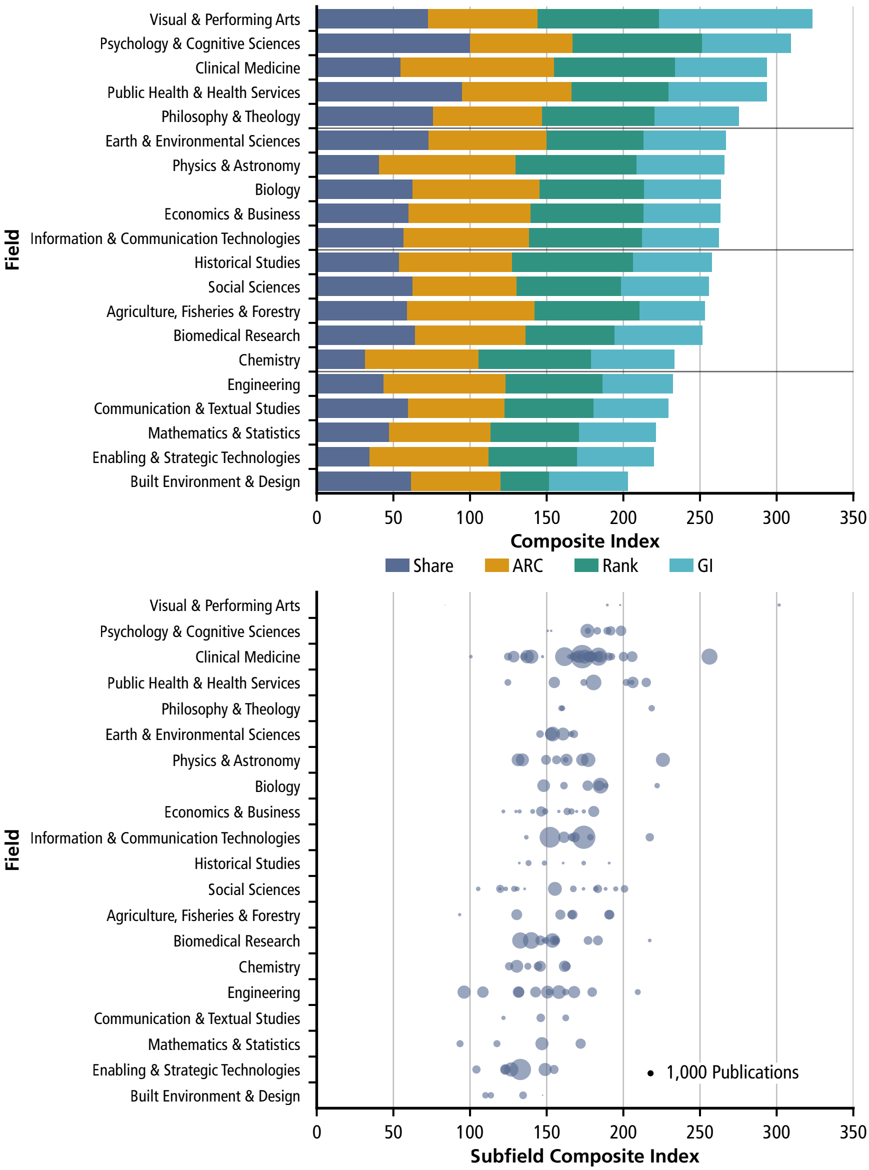
Figure 2

ARC Scores for Top 20 Countries by Number of Publications, 2003–2008 and 2009–2014

Countries are ranked by ARC score for the 2009–2014 period.

Analysis of ARC and survey rankings suggests that Canada's research strengths have remained generally stable since the 2012 CCA S&T report.

The Panel developed a composite indicator of research strength based on three dimensions: *magnitude* (based on Canada's share of world publications in that field), *impact* (based on ARC score and ARC rank), and *growth* (based on the Growth Index (GI) score, reflecting Canada's growth in research output relative to the rest of the world). Research fields can be divided into three general groups based on this indicator (Figure 3). The top quartile represents areas of



Data Source: Panel calculations based on data provided by Science-Metrix using Scopus database (Elsevier)

Figure 3

Composite Score by Research Field in Canada, 2009–2014

Composite scores are based on four indicators: ARC scores, ARC ranks, GI scores, and Canada's share of world publications in that field or subfield. Field scores (ARC, ARC rank, GI and share) were normalized relative to the other fields and subfields scores normalized relative to the other subfields. All four indicators are weighted equally. The top panel shows composite scores for fields, along with their four subcomponents. The bottom panel shows the dispersion of composite scores for subfields within each field, with the size of bubbles corresponding to the number of publications.

comparative strength for Canada: Visual and Performing Arts, Psychology and Cognitive Sciences, Clinical Medicine, Public Health and Health Services, and Philosophy and Theology. The second and third quartiles together feature a strong middle pack of Canadian fields that typically perform well on two of the three dimensions. The bottom quartile contains fields in which Canada is less competitive internationally. An analysis of composite scores at the subfield level reveals substantial variation within fields. In Philosophy and Theology and Physics and Astronomy, for example, Applied Ethics and Astronomy and Astrophysics rank much higher than the other subfields within those fields.

When it comes to research on most enabling and strategic technologies, however, Canada lags other countries. Bibliometric evidence suggests that, with the exception of selected subfields in Information and Communication Technologies (ICT) such as Medical Informatics and Personalized Medicine, Canada accounts for a relatively small share of the world's research output for promising areas of technology development. This is particularly true for Biotechnology, Nanotechnology, and Materials science. Canada's research impact, as reflected by citations, is also modest in these areas. Aside from Biotechnology, none of the other subfields in Enabling and Strategic Technologies has an ARC rank among the top five countries. Optoelectronics and photonics is the next highest ranked at 7th place, followed by Materials, and Nanoscience and Nanotechnology, both of which have a rank of 9th. Even in areas where Canadian researchers and institutions played a seminal role in early research (and retain a substantial research capacity), such as Artificial Intelligence and Regenerative Medicine, Canada has lost ground to other countries.

Trends in Industrial R&D

There has been a sustained erosion in Canada's industrial R&D capacity and competitiveness. Canada ranks 33rd among leading countries on an index assessing the magnitude, intensity, and growth of industrial R&D expenditures. Although Canada is the 11th largest spender, its industrial R&D intensity (0.9%) is only half the OECD average and total spending is declining (–0.7%). Compared with G7 countries, the Canadian portfolio of R&D investment is more concentrated in industries that are intrinsically not as R&D intensive. Canada invests more heavily than the G7 average in oil and gas, forestry, machinery and equipment, and finance where R&D has been less central to business strategy than in many other industries. However, it can be difficult to determine the implications of R&D trends for industries such as wholesale trade, which include a diverse range of firms united only by the predominance of sales and distribution activities in their business operations. About 50% of Canada's industrial R&D spending is in high-tech sectors (including industries such as ICT, aerospace, pharmaceuticals, and automotive) compared with the G7 average of 80%. Canadian Business Enterprise Expenditures on R&D (BERD) intensity is also below the OECD average in these sectors. In contrast, Canadian investment in low and medium-low tech sectors is substantially higher than the G7 average. Canada's spending reflects both its long-standing industrial structure and patterns of economic activity.

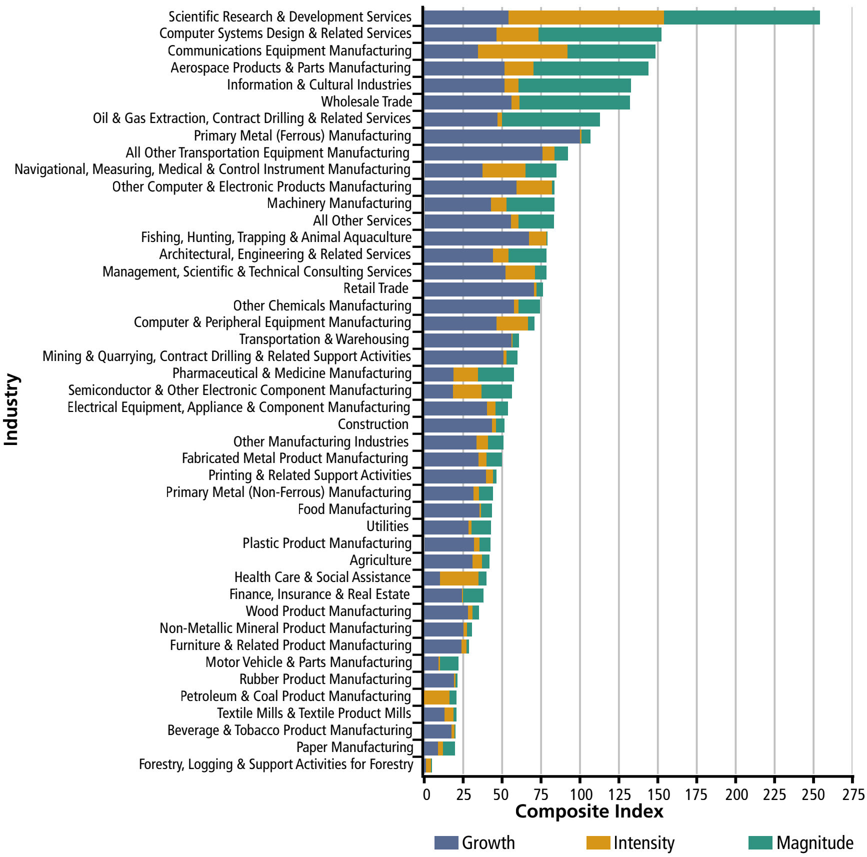
R&D investment patterns in Canada appear to be evolving in response to global and domestic shifts. While small and medium-sized enterprises continue to perform a greater share of industrial R&D in Canada than in the United States, between 2009 and 2013, there was a shift in R&D from smaller to larger firms. Canada is an increasingly attractive place to conduct R&D. Investment by foreign-controlled firms in Canada has increased to more than 35% of total R&D investment, with the United States accounting for more than half of that. Multinational enterprises seem to be increasingly locating some of their R&D operations outside their country of ownership, possibly to gain proximity to superior talent. Increasing foreign-controlled R&D, however, also could signal a long-term strategic loss of control over intellectual property (IP) developed in this country, ultimately undermining the government's efforts to support high-growth firms as they scale up.

Canada produces about 1% of global patents, ranking 18th in the world. It lags further behind in trademark (34th) and design applications (34th). Despite relatively weak performance overall in patents, Canada excels in some technical fields such as Civil Engineering, Digital Communication, Other Special Machines, Computer Technology, and Telecommunications. Canada is a net exporter of patents, which signals the R&D strength of some technology industries. It may also reflect increasing R&D investment by foreign-controlled firms.

The Panel relied on three indicators to identify industries of R&D strength: magnitude (annual average R&D expenditures between 2006 and 2015), intensity (R&D expenditures as a share of revenues between 2009 and 2013), and growth (compound annual growth between 2006 and 2015). Based on a composite indicator, the Panel classified four industries of R&D strength:

- Scientific research and development services
- Computer systems design
- Communications equipment manufacturing
- Aerospace products and parts manufacturing

Between 2006 and 2015, Canada business R&D spending grew less than both inflation and OECD average spending and recent estimates suggest further erosion. Between 2014 and 2017, Canadian business R&D is projected to decline by 2.8% per year, with more than half of this decline in oil and gas extraction and software publishing. Among the largest industries, only six increased their spending on R&D, lead by chemical manufacturing and telecommunications services. Most Canadian industries are now spending less on R&D than in the previous decade.



Data Source: StatCan, 2017a, 2017i

Figure 4

Domestic Industrial R&D Strength, Canadian Industries, 2006–2015

The figure ranks Canadian industries (NAICS) based on a composite index of industrial R&D spending: magnitude (BERD spending, average 2011–2015), intensity (BERD/GDP, average 2009–2013), and growth (BERD CAGR, 2006–2015). Each component is adjusted as a fraction of 100 implying a maximum score of 300.

This Panel was also tasked with identifying the "scientific disciplines and technological applications where Canada's relative strengths are most aligned with Canada's economic strengths/industry needs." R&D activities conducted (or contracted out) by industry inherently reflect their perceived needs. Trends in industrial R&D reflect these needs and tend to mirror Canada's industrial structure. The comparatively high level of business funding for R&D in Canadian universities, coupled with growing numbers of research partnerships between universities and businesses, does not suggest an overall deficit of connectivity between industry and academia. Regarding alignment with Canada's economic strengths, the Canadian economy is dominated by industries in which R&D is not a core component of business strategy and Canadian business R&D expenditures reflect this. Oil and gas, construction, real estate, and finance industries, for example, rely more extensively on natural resources, capital, and talent than on R&D. At the same time, Canada's technology-intensive industries such as ICT, the biopharmaceutical sector, aerospace, and the automotive industry clearly benefit from Canada's research activity and strength in related fields. Canada's research capacity in artificial intelligence (AI) technologies also could have widespread relevance across the economy. However, in the Panel's view Canada's R&D capacity remains generally underutilized by Canadian industry given the relative lack of R&D-intensive industries and major corporate R&D funders.

R&D Activity and Trends by Region

R&D investment, output, and impact are unequally distributed across Canada. Almost the entire decline in national R&D spending from 2006 to 2015 occurred in Ontario and Quebec. By contrast, R&D spending grew in most other provinces and, as such, is becoming slightly less concentrated across provinces. Despite their decreasing share of total Canadian R&D, Ontario and Quebec remain dominant. If assessed independently, they would each rank among the top 25 countries in total R&D spending.

Tremendous research diversity exists across provinces. Each province produces at least twice as many publications as the world average in at least 15 academic subfields. Ontario, Quebec, British Columbia, and Alberta are the largest centres of research activity by province. They also have the highest average and median impact, and the highest levels of growth in research output and international collaboration. Table 1 shows the top five subfields by specialization and impact (i.e., by specialization index (SI) and ARC score) for each province. Between 2003 and 2014, patent output grew in all provinces except Quebec, as pharmaceutical activity declined. Notably, all provinces except Prince Edward Island are now net exporters of patents.

Table 1
Top Five Subfields by SI and ARC Score by Province/Region, 2003–2014

Province	Top Five Subfields by SI Score	Top Five Subfields by ARC Score
British Columbia	Forestry Drama & Theatre Fisheries Geography Ornithology	General & Internal Medicine General S&T Mining & Metallurgy Nuclear & Particle Physics Astronomy & Astrophysics
Alberta	Geology Physiology Sport, Leisure & Tourism Sport Sciences Medical Informatics	General & Internal Medicine Nuclear & Particle Physics Anatomy & Morphology Mining & Metallurgy General Physics
Prairies	Ornithology Veterinary Sciences Agronomy & Agriculture Agricultural Economics & Policy Physiology	General & Internal Medicine Nuclear & Particle Physics Surgery Allergy Electrical Engineering
Ontario	Drama & Theatre Rehabilitation Gender Studies Criminology Experimental Psychology	General & Internal Medicine Nuclear & Particle Physics Gastro & Hepatology Respiratory System Dermatology
Quebec	Forestry Econometrics Industrial Relations Developmental Psychology Experimental Psychology	General & Internal Medicine Anatomy General Physics Music Nuclear Physics
Atlantic Provinces	Veterinary Fisheries Oceanography Horticulture History	General & Internal Medicine Dermatology Food Science Design & Management Mechanical Engineering

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

Canadian R&D capacity is concentrated in cities, particularly Toronto, Montréal, Vancouver, Ottawa, and Calgary. These five cities create patents and high-tech companies at nearly twice the rate of other cities. They also account for half of all clusters in the services sector (e.g., ICT, finance) and many clusters in advanced manufacturing. Many R&D clusters in Canada relate to natural resources and long-standing areas of economic and research strength. Natural resource clusters have emerged around the location of resources, such as forestry in British Columbia, oil and gas in Alberta, agriculture in Ontario, mining in Quebec, and maritime resources in Atlantic Canada. The automotive, plastics, and steel industries have the most individual clusters because of these industries' economic success in Windsor, Hamilton, and Oshawa. Advanced manufacturing industries, such as aerospace, life sciences, and ICT manufacturing, tend to be more concentrated, often located near specialized research universities.

Linking R&D, Innovation, and Wealth Creation

Canada's combination of high performance in measures of research output and impact, and low performance on measures of industrial R&D investment and innovation (e.g., subpar productivity growth), continue to be viewed as a paradox, leading to the hypothesis that barriers are impeding the flow of Canada's research achievements into commercial applications. The Panel's analysis suggests the need for a more nuanced view. The process of transforming research into innovation and wealth creation is a complex multifaceted process, making it difficult to point to any definitive cause of Canada's deficit in R&D investment and productivity growth. Based on the Panel's interpretation of the evidence, Canada is a highly innovative nation, but significant barriers prevent the translation of innovation into wealth creation. The available evidence does point to a number of important contributing factors that are analyzed in this report. Figure 5 represents the relationships between R&D, innovation, and wealth creation.

The Panel concluded that many factors commonly identified as points of concern do not adequately explain the overall weakness in Canada's innovation performance compared with other countries. Academia-business linkages appear relatively robust in quantitative terms given the extent of cross-sectoral R&D funding and increasing academia-industry partnerships, though the volume of academia-industry interactions does not indicate the nature or the quality of that interaction, nor the extent to which firms are capitalizing on the research conducted and the resulting IP. The educational system is high performing by international standards and there does not appear to be a widespread lack of researchers or STEM (science, technology, engineering, and mathematics) skills. IP policies differ across universities and are unlikely to explain a divergence in research commercialization activity between Canadian and U.S. institutions, though Canadian universities and governments could do more to help Canadian firms access university IP and compete in IP management and strategy. Venture capital availability in Canada has improved dramatically in recent years and is now competitive internationally, though still overshadowed by Silicon Valley. Technology start-ups and start-up ecosystems are also flourishing in many sectors and regions, demonstrating their ability to build on research advances to develop and deliver innovative products and services.

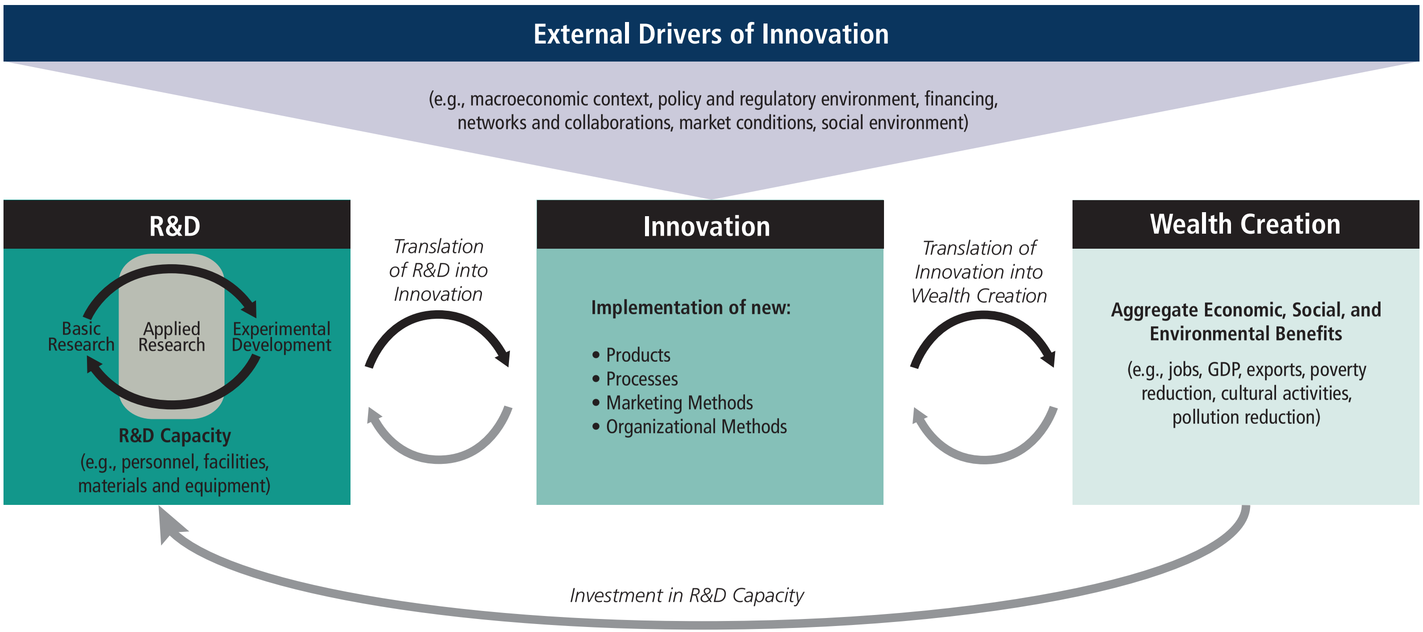


Figure 5

The Links Between R&D, Innovation, and Wealth Creation

The translation of R&D into innovation and wealth creation is complex, occurring through distinct stages. Advances in basic research and experimental development are mutually supportive (linked, in many cases, through applied research). R&D feeds into innovation by supporting the creation of new products, processes, and marketing or organizational methods. This report focuses primarily on product and process innovation as those types of innovation are more closely linked to R&D and technology development. Innovations are also fed by external drivers such as macroeconomic context, policy, regulatory or social environments. Innovations lead to economic benefits through productivity increases, job creation, GDP growth, etc. Innovations may also provide other social benefits, such as reducing environmental impacts or improving the efficiency or effectiveness of public services.

Growing start-up firms into large, mature, and sustainable businesses involves significant challenges that are hindering technology firms from scaling up domestically in Canada. Although macroeconomic conditions and the regulatory environment appear to be conducive to business creation and development, Canada's promising start-ups are often acquired and developed in other countries, leading to a loss of economic and commercial benefits. This trend is driven by many factors including the larger size of the U.S. market, the structure and nature of capital markets in Canada, and the rapidly growing interest of China in Canadian commercial activities. The fact that Canada's R&D tax credits are more competitive for smaller firms than for large corporations suggests that Canada is a better place to start a technology company than to grow one. Survey evidence from Canadian firms and technology stakeholders also suggests that a lack of managerial talent and experience in growing domestic technology firms to scale is a critical impediment.

Conclusion

Canada's mostly undiminished capacity for high-quality research and extensive pools of research talent are a legacy of past investments. Canada remains home to world-leading researchers, facilities, and programs, and their accomplishments and importance continue to be regarded with much esteem by the international community. A broad base of research talent, a stable macroeconomic context, a diverse and welcoming social environment, and a history of seminal R&D contributions are Canada's most important R&D strengths. Together, they could serve as the foundation for a future where Canada continues to produce world-leading research and counts among the most innovative and productive economies. Currently, however, that future is threatened. Declining levels of private and public R&D expenditures threaten to erode Canada's research capacity over time. The loss of innovative start-ups to foreign buyers, and the inability to grow a sufficient number of start-ups to scale, means that Canadians do not fully capture the social and economic benefits stemming from Canadian research advances. Furthermore, recent developments suggest a growing risk of foreign-based technology companies capturing a disproportionate share of the benefits of past government investments in R&D. While some of the commercial benefits of that R&D may remain in Canada, there is also a risk that a fair proportion of it will be developed offshore. Addressing these challenges requires overcoming the inertia inherent in current, anemic patterns of institutional support for R&D in Canada. Success is not assured. However, the potential gains from an improved state of R&D in Canada in the future would make it well worth the effort.

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Glossary of Key Terms

Academia: Constitutes the span of post-secondary education in universities, colleges, institutes of technology, cégeps, and polytechnics, which perform HERD (higher education expenditures on research and development).

Applied Research: This research is original investigation undertaken to acquire new knowledge, but directed primarily towards a specific, practical aim or objective (OECD, 2015b).

Average Relative Citations (ARC): This indicator measures the impact of publications produced by a given entity as reflected in citations. An ARC score over 1.0 indicates that the entity publishes publications that are more highly cited than the world average. ARC scores are normalized by publication type, year, and field of research. ARC scores (along with other measures of impact) are less reliable for fields or entities producing low numbers of publications, as the score can be driven by outliers.

Basic Research: This research is observational, experimental, or theoretical work undertaken primarily to acquire new knowledge of the underlying foundations of phenomena and observable facts, without any particular application or use in mind (OECD, 2015b).

Business Enterprise Expenditures on Research and Development (BERD): BERD represents the component of GERD incurred by units belonging to the business enterprise sector. It is the measure of intramural R&D expenditures within the business enterprise sector during a specific reference period (OECD, 2015b).

Collaboration Index (CI): Based on publication co-authorships, the CI indicator measures the level of collaboration of a given entity with another entity in the context of the entity's total publications (countries producing more publications tend to collaborate less internationally, given their increased potential for internal collaboration). A collaboration score over 1.0 means that the entity collaborates more than expected given its total publication output.

Experimental Development: This systematic work draws on knowledge gained from research and practical experience and produces additional knowledge, which in turn is dedicated to creating new products or processes or to improving existing products or processes (OECD, 2015b).

Government Intramural Expenditures on R&D (GOVERD): GOVERD represents the component of GERD incurred by units belonging to the government sector. It is the measure of expenditures on intramural R&D within the government sector during a specific reference period (OECD, 2015b).

Gross Domestic Expenditures on Research and Development (GERD): GERD is the total intramural expenditure on research and development performed in the national territory during a given period (OECD, 2015b).

Gross Domestic Product (GDP): GDP is the sum of gross value added by all resident producers in the economy, including distributive trades and transport, plus any product taxes and minus any subsidies not included in the value of the products (UNESCO, 2018).

Growth Index (GI): GI score measures the growth of publications between two periods of time (2003–2008 and 2009–2014 in this report) relative to the growth of a reference entity (e.g., the world) for the same period of time. For example, if Canada's GI is above 1.0 for a specific field or subfield, it means that Canada's publication output in that field or subfield is growing faster than the world average.

Growth Rate (GR): The GR indicator simply corresponds to the percentage change in total publication output between two periods; a GR score of 1.37, for example, indicates that output increased by 37% between two periods.

Higher Education Expenditures on Research and Development (HERD): HERD represents the component of GERD incurred by units belonging to the higher education sector. It is the measure of intramural R&D expenditures within the higher education sector during a specific period (OECD, 2015b).

Highly Cited Publications (HCP1%): HCP1% is a measure of research impact based on the upper tail of the distribution of normalized citation counts. The top-cited 1% of publications are identified by field or subfield for a given period. A value above 1.0 indicates that the entity has more highly cited publications than expected based on its share of all publications in that field or subfield. For example, if Paleontology in Canada represented 1% of global publications but 2% of highly cited publications, its HCP1% value would be 2.0.

Innovation: The implementation of a new or significantly improved product (good or service) or process, a new marketing method, or a new organizational method in business practices, workplace organization, or external relations (OECD/Eurostat, 2005).

Industrial R&D: R&D activities and related variables undertaken by companies and industrial not-for-profit organizations. Statistics Canada uses this term for collecting and reporting R&D data from the private sector; it is synonymous with R&D activities in the business enterprise sector as reported by the OECD (see BERD).

Infrastructure: A base of research facilities, equipment, and infrastructure that can support researchers advancing the frontiers of knowledge in their fields.

Patent Flow: Patent flow provides a partial picture of how patents in Canada are exploited. A negative flow represents a deficit of patented inventions owned by Canadian assignees versus the number of patented inventions created by Canadian inventors.

Median Relative Citations (MRC): MRC is similar to ARC and is also a measure of research impact based on field-normalized citations. However, MRC is calculated with reference to the median score rather than to the average. It is arguably a better measure of the central tendency in most areas of research given that citation distributions tend to be skewed, with a small number of publications attracting large numbers of citations.

Number of Publications: This measures the publication count for a given entity such as a country, a province, or a research field. Publication counts can be presented in whole and fractional counts. With whole counting, each publication is counted once for each unit with a participating author. For example, if a publication is co-authored by two researchers from different countries, the publication is counted once for each country. With fractional counting, each co-author (and associated entity) is credited with a fraction of a publication corresponding to the number of authors. In the preceding example, each researcher (and country) is allotted one-half of a publication.

Research and Experimental Development (R&D): R&D comprises creative and systematic work undertaken to increase the stock of knowledge — including knowledge of humankind, culture, and society — and to devise new applications of available knowledge. It includes basic research, applied research, and experimental development (OECD, 2015b).

Small and Medium-Sized Enterprises (SMEs): SMEs are non-subsidiary, independent firms that employ fewer than a given number of employees. This number varies across countries. The most frequent upper limit designating an SME is 250 employees, as in the European Union. However, some countries set the limit at 200 employees, while the United States considers SMEs to include firms with fewer than 500 employees. In Canada, SMEs are defined as enterprises with less than 250 employees and less than $50 million in total revenue.

Specialization Index (SI): This indicator is a measure of the relative research intensity for an entity in a specific field of research. An SI score greater than 1.0 means that more publications were published in a given field or subfield than would be expected based on world averages. For example, if publications in Physics and Astronomy account for 10% of a country's total publications, but only 5% of total world publications, that country would have a high SI score in that field. Conversely, an SI score below 1.0 means that less research is produced than expected based on world averages.

Tri-Agency: The Tri-Agency is composed of the Canadian Institutes of Health Research (CIHR), the Natural Sciences and Engineering Research Council of Canada (NSERC), and the Social Sciences and Humanities Research Council (SSHRC).

Selected Abbreviations and Acronyms Used in the Report

ARC	Average Relative Citations
BERD	Business Enterprise Expenditures on R&D
CFI	Canada Foundation for Innovation
CI	Collaboration Index
CIFAR	Canadian Institute for Advanced Research
CIHR	Canadian Institutes of Health Research
GDP	gross domestic product
GERD	Gross Domestic Expenditures on R&D
GI	Growth Index
GOVERD	Government Intramural Expenditures on R&D
GR	Growth Rate
HERD	Higher Education Expenditures on R&D
IP	intellectual property
ISED	Innovation, Science and Economic Development Canada
MFP	multifactor productivity
MRC	Median Relative Citations
NSERC	Natural Sciences and Engineering Research Council
OECD	Organisation for Economic Co-operation and Development
R&D	research and experimental development
S&T	science and technology
STEM	science, technology, engineering, and mathematics
SI	Specialization Index
SSHRC	Social Sciences and Humanities Research Council
VC	venture capital

1

Introduction

- Charge to the Panel
- A Comment on Scope and Terminology
- Research Approach and Methodology
- Comparison with Canada's Fundamental Science Review
- Report Structure

1 Introduction

Canada has made lasting contributions in virtually every field of research, advancing the frontiers of knowledge and enhancing human well-being in the process. A well-known example in medicine is the discovery of insulin by Frederick Banting and Charles Best in 1922. Later, Freda Miller discovered that skin can be a viable source of stem cells. On the technology side, the invention of the charge-coupled device by Willard Boyle in Bell Labs made possible the imaging technology used in digital cameras today. Researchers in Canada have made advances in plate tectonics (John Tuzo Wilson in the 1970s), meteorology (revolutionized by Roger Daley's work on computerized forecasting systems), chemistry (Gerhard Hertzberg's research on free radicals), historical studies (Margaret MacMillan's teachings on international relations), and physics (Arthur McDonald's research on neutrinos). They have contributed to the development of iconic and transformative technologies such as the telephone and smartphone, pacemaker, and touchscreen. Meanwhile, communities of technology start-ups are thriving in many Canadian cities, building on research advances and introducing new products, processes, and services into the market.

Despite this record of past achievements, however, Canada cannot afford to be complacent about its place in the global research and experimental development (R&D) and innovation landscape. Most countries are now aware of how much their future competitiveness and prosperity depend on (i) the extent to which they develop and maintain their capacity to participate in cutting-edge discovery, development, and innovation; and (ii) a workforce with the skills and knowledge needed to deploy and adopt the latest ideas and technologies. These include not only technical skills, but also knowledge and understanding of the social, economic, cultural, and political contexts in which new ideas are adopted and pressing social challenges to which countries are confronted. Emerging economies see the development of their R&D and innovation potential as essential to their continued economic development. This view is powerfully evident in the rapid increases in China's research output and impact over the past two decades. As R&D and innovation activities become more globalized, a growing pool of institutions is competing to attract top talent to harness the benefits of innovation and improve their citizens' well-being.

Ensuring that Canada remains competitive in the global R&D and innovation landscape also requires periodic assessments of the latest evidence on R&D and innovation performance. Those engaged in developing policies on research and innovation need access to a broad spectrum of supporting information, data, and indicators, ranging from measures of research and technology trends to indicators of the commercial context for innovation (NRC, 2014). Regional differences and the geographic distribution of R&D and innovation activities matter, especially in a federation with a large land mass. To best support innovation, policies must reflect the complex web of factors that influence the extent to which R&D is mobilized to yield economic and social benefits. The first requirement for improving Canada's R&D and innovation performance is consequently an understanding of national and regional R&D trends and how these trends are situated in a global context.

1.1 CHARGE TO THE PANEL

In response to previous requests from the Minister of Industry, the Council of Canadian Academies (CCA) has published two reports titled *The State of Science and Technology in Canada*, the first in 2006 (CCA, 2006) and another in 2012 (CCA, 2012a). These two reports provide a snapshot in time of science and technology (S&T), understanding S&T to encompass Canadian activity in all fields of research and technology development, including the natural sciences and mathematics, health sciences, engineering, social sciences, humanities, and arts and design. In 2012, the Minister of Industry asked the CCA to separately assess the state of industrial R&D in Canada (i.e., R&D carried out in the private sector), which resulted in the release of *The State of Industrial R&D in Canada* in 2013 (CCA, 2013b).[1]

In June 2016, the Minister of Science asked the CCA to update its previous assessments on S&T and industrial R&D in Canada. Combining the charges from 2012 and 2013, a new Expert Panel on the State of Science and Technology and Industrial Research and Development in Canada (the Panel) was appointed to address the following question and sub-questions:

> *What is the current state of science and technology (S&T) and industrial research and development (R&D) in Canada?*
>
> - *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, and why? Which scientific disciplines and technological applications have the potential to emerge as areas of prominent strength for Canada?*

1 These reports are referred to as the *2006 S&T report*, the *2012 S&T report*, and the *2013 industrial R&D report*, respectively throughout this report.

- *What are the existing industrial R&D strengths in Canada? How are these strengths distributed by sector and 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 are our relative strengths most aligned with Canada's economic strengths/industry needs?*

- *What are the key barriers and knowledge gaps in translating Canadian strengths in S&T into innovation and wealth creation?*

The Panel, composed of individuals with a range of multidisciplinary and multisectoral expertise, met in-person four times and several times by teleconference to identify, assess, and interpret evidence and deliberate on its charge. This report is the final product of those deliberations.

1.2 A COMMENT ON SCOPE AND TERMINOLOGY

Terms such as *science*, *research and development*, *technology*, and *innovation* are commonly used, and yet also frequently the source of confusion. In the CCA's 2006 S&T report, the term *science and technology* or *S&T* referred to research pursuits and technological developments encompassing all fields of inquiry (including the social sciences, humanities, and arts) and all activities along the spectrum from basic research to technology development (CCA, 2006). In 2012 and 2013, when the federal government made two separate requests to the CCA, the implication was that S&T occurred primarily in the higher education sector whereas industrial R&D occurred in the private sector.

While respecting the need for continuity in tracking Canada's research performance, this Panel adopted different core terms. The association of S&T exclusively with academic research is problematic and was an unintended artefact of the division created in 2012 and 2013 with the dual requests from government. S&T is also sometimes narrowly associated with activity in the natural sciences, health sciences, and engineering (particularly with respect to basic research). This makes it less appropriate for an assessment that includes the social sciences, humanities, and arts. For this report, the Panel opted to use the more inclusive term *research and experimental development* (R&D), perceiving this usage as more consistent with the latest international practices.[2]

2 This approach to terminology is also consistent with the use of *research* by the Advisory Panel for *Canada's Fundamental Science Review*, which encompasses science and all other fields of scholarly inquiry (Advisory Panel for the Review of Federal Support for Fundamental Science, 2017).

As with *S&T* in the previous reports, *R&D* is understood here to include the full range of research activities in Canada, spanning all fields of study, encompassing all stages of research and technology development, and performed in all sectors (i.e., academia, government, industry, not-for-profit sector). To analyze internationally comparable data, the Panel relied on standard technical definitions of *R&D* and related terms (e.g., basic research, applied research) as defined by the Organisation for Economic Co-operation and Development (OECD) (Box 1.1).[3]

Box 1.1
OECD Definitions of R&D and Innovation

Research and experimental development (R&D): R&D comprises creative and systematic work undertaken to increase the stock of knowledge — including knowledge of humankind, culture, and society — and to devise new applications of available knowledge.

- **Basic research:** Observational, experimental, or theoretical work undertaken primarily to acquire new knowledge of the underlying foundations of phenomena and observable facts, without any particular application or use in mind.
- **Applied research:** Original investigation undertaken to acquire new knowledge, but directed primarily towards a specific, practical aim or objective.
- **Experimental development:** Systematic work that draws on knowledge gained from research and practical experience and produces additional knowledge, which in turn is dedicated to creating new products or processes or to improving existing products or processes.

Innovation: The implementation of a new or significantly improved product (good or service) or process, a new marketing method, or a new organizational method in business practices, workplace organization, or external relations.

From OECD, 2015b; OECD/Eurostat, 2005

3 For the same reason, the term *basic research* is preferred over synonyms such as *discovery research* or *fundamental research.*

The final sub-question in the Panel's charge also refers to *innovation*. Innovation is not the central focus of this report; however, it falls within the Panel's mandate to consider how Canada's R&D strengths are translated into innovation and wealth creation. It is critical to recognize that R&D and innovation are not synonymous. At the most basic level, innovation consists of the introduction of new products, processes, organizational methods, or marketing methods. Much innovation is unrelated to R&D or technology, for example, when a firm's internal reorganization increases its efficiency. R&D and innovation are linked, however, as R&D is an input and driver of technological innovation (i.e., the development of new technologies that form the basis of new goods, services, and processes).[4] The Panel adopted a broad and inclusive understanding of innovation throughout its discussions, yet also relied on standardized data and definitions from the OECD for international comparisons. See Chapter 6 for more discussion about the relationship between R&D, innovation, and wealth creation.

1.3 RESEARCH APPROACH AND METHODOLOGY

In developing this report, the Panel relied on evidence from multiple sources, including a literature review and data extracted from statistical agencies and organizations such as Statistics Canada and the OECD. Relevant studies and reports, which were identified through an iterative process that built on key references identified by Panel members, include academic articles from peer-reviewed journals, reports from government departments and international organizations (i.e., grey literature), and credible studies from not-for-profit organizations, consultants, and industry associations. A formal peer review process was also carried out to ensure the quality, rigour, and objectivity of the Panel's report. Comments were received from 11 reviewers, all of which were considered by the Panel and many of which led to the incorporation of new evidence.

For international comparisons, the Panel focused on OECD countries along with selected developing countries that are among the top 20 producers of peer-reviewed research publications, such as China, India, Brazil, Iran, and Turkey. The countries included in any given table or figure vary, however, depending on the data available. For R&D expenditures and related variables, data from India, Iran, and Turkey are often lacking. For some series, differences in the methods used to collect data by national statistical agencies also result in the omission of specific countries.

4 R&D is sometimes classified as one type of *innovation activity*, with others including capital investment and training. Non-R&D innovation inputs tend to be poorly measured, which is one reason why the two concepts are routinely conflated. A current review of the challenges associated with measuring innovation and related concepts can be found in NASEM (2017).

In addition to the literature review, two primary research methods informed the Panel's assessment:

- a comprehensive bibliometric and technometric analysis of Canadian research publications and patents; and
- a survey of the world's top-cited researchers.

1.3.1 Bibliometric and Technometric Analysis

Building on the CCA's 2012 S&T report, the Panel performed a comprehensive analysis of Canada's research publications between 2003 and 2014. Data were extracted from Elsevier's Scopus database and analyzed by Science-Metrix in July and August 2016. Scopus was selected as the source of data due to its more extensive coverage of publications in the social sciences and humanities, including book chapters and book series.[5] The analysis was based on a taxonomy of research fields, developed by Science-Metrix, consisting of 22 fields and 176 subfields (Table A.1 in the appendix).[6] To identify trends over time, the analysis was designed to be comparable to that undertaken for the 2012 S&T report. It relies on the same data source, the same taxonomy of fields and subfields, and many of the same indicators, though data for some new indicators were also developed.

The CCA commissioned an analysis of Canadian patenting trends based on data from the United States Patent and Trademark Office (USPTO). The USPTO was selected both to be comparable to previous analyses and because it is the dominant location for Canadian patent filings.[7] Analysis of these data includes indicators similar to those calculated for bibliometric data, including measures of impact (e.g., Average Relative Citations or ARC) based on patent citations.[8]

Results from these analyses, as well as additional information on the indicators used and the data limitations, are presented in Chapter 3 and in the report appendix.

5 The Scopus data used for this study include three publication types: peer-reviewed journal articles, conference proceedings, and book series. Journal articles account for 80% of the publications, conference proceedings 16%, and book series the remainder.

6 The appendix for this report is available on the CCA's website at www.scienceadvice.ca.

7 For the 2010–2015 period, Canadian organizations and individuals held nearly 38,000 patents in the USPTO database, compared with about 17,000 patents in the Canadian Intellectual Property Office (CIPO) database and about 6,400 patents in the European Patent Office database.

8 While useful for quantitative analysis of R&D trends, patents are only one measure among many related to applied R&D outputs and intellectual property (IP). Chapter 4 also analyzes related data on trademarks, copyrights, and industrial designs.

1.3.2 International Survey of Top-Cited Researchers

A second source of evidence used by the Panel is a survey of the world's top-cited researchers. As with the 2012 S&T report, the CCA developed and commissioned a survey of researchers' perceptions of Canada's research strength in their field or subfield relative to that of other countries. In August 2016, with the assistance of EKOS Research, the survey was distributed to the authors of the top 1% of the most highly cited journal articles in their fields of study between 2004 and 2013 (referred to in this report as *top-cited researchers*). The survey was successfully sent to 41,470 researchers located in all countries, and 5,547 completed responses were received. Survey results and their limitations are discussed further in Chapter 3 and the full survey questionnaire is available upon request.

1.4 COMPARISON WITH CANADA'S FUNDAMENTAL SCIENCE REVIEW

On April 10, 2017, an independent panel of experts convened by the federal government released a review of federal support for fundamental (i.e., basic) science in Canada called *Investing in Canada's Future* (referred to as *Canada's Fundamental Science Review* in this report) (Advisory Panel for the Review of Federal Support for Fundamental Science, 2017). That Advisory Panel, chaired by David Naylor, provided a thorough assessment of Canada's basic science performance and its underlying institutional and financial support mechanisms. It also offered a number of recommendations to government, including the creation of a National Advisory Council on Research and Innovation, and an immediate and sustained increase in federal funding for independent, investigator-led research.

This CCA report shares common ground with *Canada's Fundamental Science Review.* For example, both reports evaluate recent R&D investment trends in Canada and arrive at similar conclusions about the threats posed by those trends. Both also assess research performance in Canada. *Canada's Fundamental Science Review* drew on preliminary data gathered for this assessment, which was published as a preliminary data update in December 2016 (CCA, 2016). Many of those data are reproduced in this report, though here they are supplemented with more analysis and additional data on patents and other forms of research output. While there are minor differences in the interpretation of data between the two reports, the major results and trends are consistent and speak for themselves.

The Advisory Panel for *Canada's Fundamental Science Review* was tasked with assessing federal support for basic science and did so through a comprehensive review of relevant programs of the granting councils and other organizations.

In contrast, evaluating the effectiveness or adequacy of federal support for research was not part of the CCA Panel's remit and it made no attempt to do so. The CCA Panel also refrained from considering governance-related issues pertaining to institutional support for science and, in keeping with CCA practice, did not make policy recommendations. This assessment, however, does offer an analysis of federal research partnership programs, regional trends in R&D performance in Canada, and barriers to the translation of research into innovation and wealth creation — subjects not touched on in *Canada's Fundamental Science Review*. The reports are therefore complementary, and together provide insights encompassing most aspects of R&D and innovation in Canada today.

1.5 REPORT STRUCTURE

The remainder of this report is structured as follows: **Chapter 2** reviews trends in research investment and capacity in Canada, including measures related to infrastructure, people, and partnerships. **Chapter 3** surveys evidence on Canada's research output and impact, such as trends in the production of publications and patents, and their impact as assessed through citations. It also identifies Canada's research strengths and outlines evidence on Canada's international reputation using survey data. **Chapter 4** compares Canada with G7 and other OECD countries in industrial spending on applied R&D, patenting, and productivity. It identifies areas of industrial R&D strength and profiles the four industries that were identified as strengths in the 2013 industrial R&D report. **Chapter 5** examines similar trends but with a regional focus, identifying patterns in the distribution of Canada's research activities across provinces and institutions. **Chapter 6** assesses evidence on the translation of Canada's R&D strengths into innovation and wealth creation, exploring the barriers impeding this process. **Chapter 7** summarizes the Panel's final conclusions on its charge.

2

R&D Investment and Capacity

- R&D Investment
- Education and R&D Personnel
- R&D Infrastructure
- Conclusion

2 R&D Investment and Capacity

Key findings

Declining R&D investment is eroding Canada's international standing.

- There was virtually no growth in Canada's total R&D expenditures between 2006 and 2015, and R&D as a share of GDP has consistently declined since 2001. Canada would need to more than double expenditures to equal the R&D intensity of world-leading countries.
- Low and declining business R&D expenditures are the primary driver of this trend; however, government R&D is also falling in real terms.
- While still high compared to most countries, R&D expenditures in the higher education sector in Canada increased more slowly than the OECD average between 2006 and 2015.

Canada's R&D expenditures are more concentrated in the higher education sector than in other OECD countries.

- Although the proportion of business-funded R&D in the higher education sector is relatively high and the number of academia-business research partnerships is increasing, total business funding for R&D in the sector has not increased since 2007.

Canada compares favourably with other countries on most measures of research skills and education, but the number of R&D personnel employed in industry is falling.

- Canada's population has the highest level of educational attainment in the OECD, but among younger cohorts (aged 25 to 34), Canada now lags behind Japan and South Korea.
- The number of full-time researchers in Canada increased modestly between 2004 and 2012, but the number of business R&D personnel dropped by 20% between 2008 and 2013.

Canada continues to be home to world-leading infrastructure, facilities, and programs in many research fields, but declining R&D investment will erode the competitiveness of research infrastructure in Canada.

- 60% of surveyed top-cited researchers reported that Canada hosts world-leading infrastructure or programs in their field, an increase of 4 percentage points since 2012.

This chapter compares Canada's R&D investment and capacity to those of peer countries and highlights key trends and their implications. In the Panel's view, a country's capacity to undertake world-leading R&D rests on three pillars:

- *investment:* an adequate and sustainable flow of R&D investment;
- *people:* researchers, technicians, and personnel with the skills and experience necessary to drive cutting-edge research and adopt the latest technologies; and
- *infrastructure:* a base of research facilities and equipment that can support researchers advancing the frontiers of knowledge in their fields.

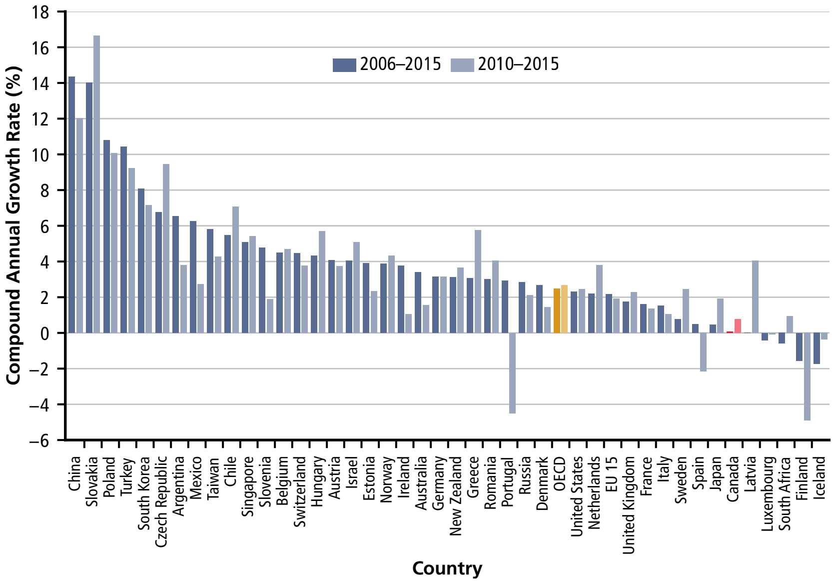
The following sections review evidence on the state of these pillars in Canada using recent data collected by Statistics Canada and the OECD.

2.1 R&D INVESTMENT

Most countries now view national investment in R&D as central to maintaining their economic competitiveness. According to the U.S. National Science Board, global R&D spending doubled from US$836 billion in 2003 to approximately US$1.67 trillion in 2013 (NSB, 2016). It grew at an annual rate of 5.7% between 2008 and 2013, and of 7.2% between 2003 and 2013. Growth in R&D spending in China was particularly dramatic, with an average annual growth rate of 19.5% between 2008 and 2013. In 2013, China accounted for about 20% of R&D spending worldwide, which has shifted the global R&D landscape. The shares of the United States and Europe have declined despite annual growth rates in R&D spending of about 5%, between 2003 and 2013 (NSB, 2016).

The contrast between global and Canadian trends is stark. Total R&D spending in Canada (Gross Domestic Expenditures on R&D, or GERD) in 2015 was $31.8 billion (StatCan, 2017g). However, adjusted for inflation, total R&D spending in Canada mostly remained stable between 2006 and 2015 (Figure 2.1). Canada is one of only a few OECD countries[9] with a compound annual growth rate close to 0% for this time period. While Canadian R&D spending remained flat taking inflation into account, total R&D investment across OECD countries increased at a rate of 2.5% per year between 2006 and 2015 (OECD, 2016a).

9 OECD countries are Australia, Austria, Belgium, Canada, Chile, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, South Korea, Latvia, Luxembourg, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom, and United States.



Data Source: OECD, 2016a

Figure 2.1

Compound Annual Growth in R&D Spending by Country, 2006–2015

Canada is one of few countries in the OECD with virtually no growth in R&D spending between 2006 and 2015. On average, R&D spending grew across the OECD at a rate of 2.5% per year during this period. In Canada, it grew only at a rate of 0.1%. Growth rates are based on compound annual growth in GERD in constant prices (i.e., adjusted for inflation). The EU15 represents: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, and United Kingdom.

Canada's R&D intensity or R&D as a share of gross domestic product (GDP) has also continued to decline as R&D investment failed to keep pace with economic growth. The ratio of national R&D investment to GDP in Canada fell from 2.0% in 2001 to 1.7% in 2015. Meanwhile, the gap between Canada and other OECD countries has widened (Figure 2.2). In 2015, the levels of R&D investment of global leaders (Israel and South Korea) were over 4% of GDP, while the OECD average stood at 2.4%. To put this into perspective, if Canada's national R&D expenditures were to immediately double, they would be approximately equal to current levels of R&D investment (as a share of GDP) of Switzerland, Japan, and Sweden, and still below that of Israel and South Korea.

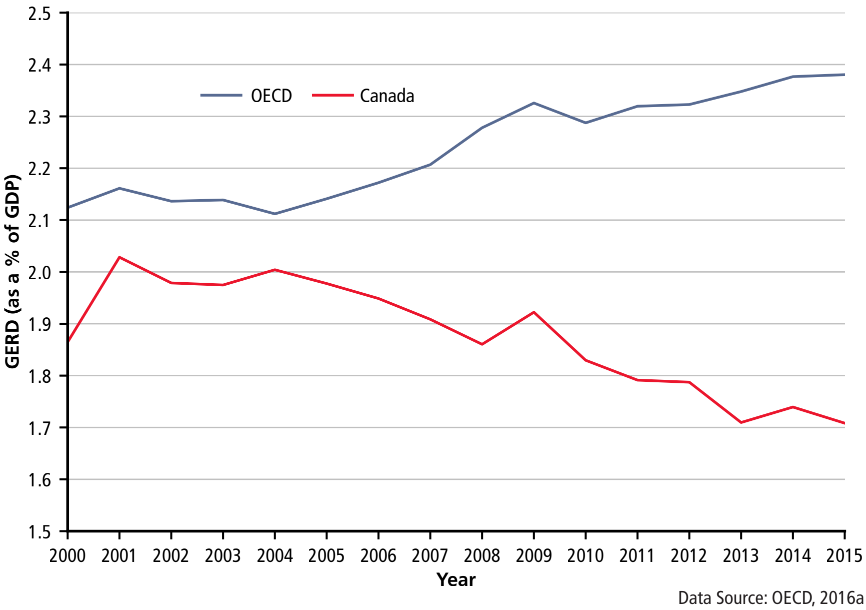


Figure 2.2

R&D Intensity in Canada and OECD Countries, 2000–2015

Canada's R&D intensity (GERD as a share of GDP) has declined steadily since peaking in 2001. Across OECD countries, however, R&D spending relative to GDP has continued to increase. The OECD average is now 2.4% of GDP and leading countries have R&D intensities above 4%. Note that the GERD for Canada for years 2014 and 2015 are based on a new Statistics Canada methodology and the increase between these two years is likely due to the introduction of the new methodology.

2.1.1 Investment Trends by Research Performer

Canada's R&D spending is more highly concentrated in the higher education sector than is typical in the OECD and other peer countries (Figure 2.3). Relative to GDP, R&D performed in this sector in Canada was 0.66% in 2015, compared with an OECD average of 0.42%. Canada ranked seventh in the OECD by this measure in 2015, and first among G7 countries (OECD, 2016a). Conversely, the amount of R&D performed in Canada's business sector is much lower than in other peer countries. As a share of GDP, Business Enterprise Expenditures on R&D (BERD) in Canada in 2015 were just over half the OECD and G7 averages (excluding Canada), and less than one-third of that of R&D leaders such as South Korea. By this measure, 2015 Canada ranked 20th among OECD countries (OECD, 2016a). The share of R&D performed by Canada's federal government is also low, at approximately 60% of the OECD average (Figure 2.3). The preponderance of R&D in the higher education sector in Canada can be partially explained by the fact that a relatively large share of university R&D is financed by industry (Figure 2.4). However, even taking that into account, Canada's total business investment in R&D remains well below the OECD average.

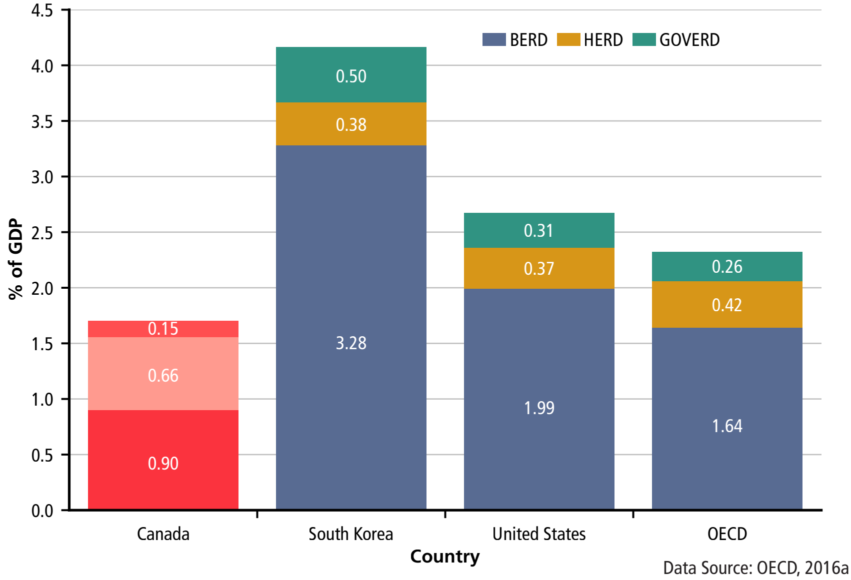


Figure 2.3

BERD, HERD, and GOVERD as a Percentage of GDP for Selected Countries, 2015

Canada's industrial R&D expenditures are particularly low as a share of GDP, and government R&D expenditures are also comparatively low. Canada's level of R&D expenditures in the higher education sector, however, remains higher than that of most OECD countries. GOVERD refers to Government Intramural R&D Expenditures. Values are for R&D by the sector in which it is performed.

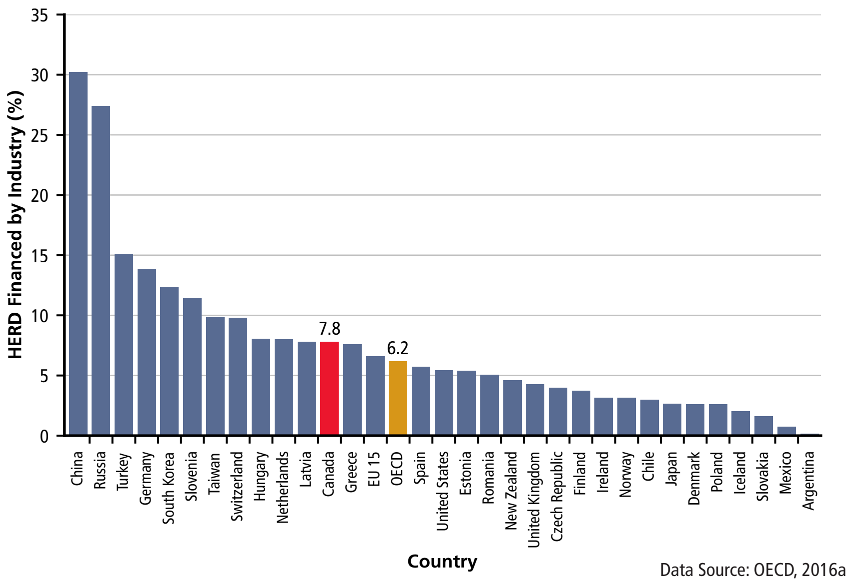


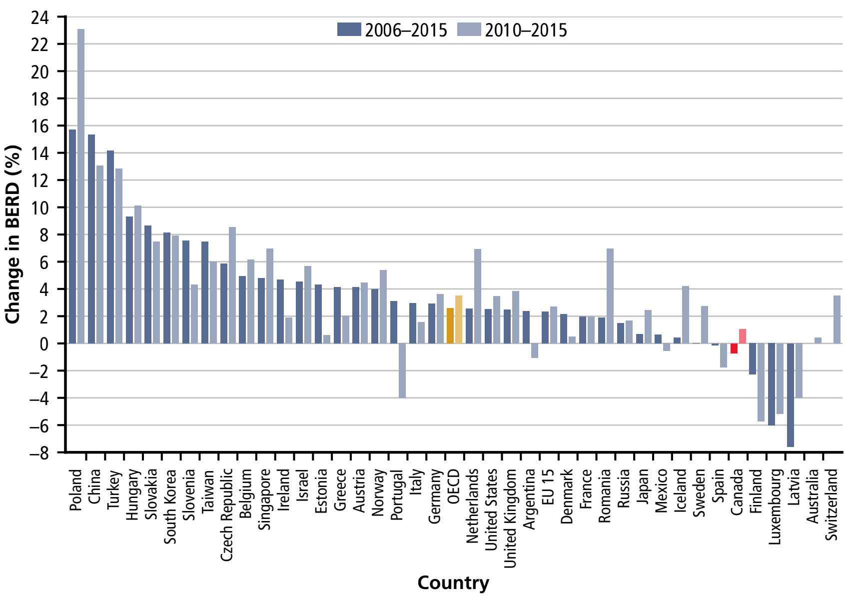
Figure 2.4

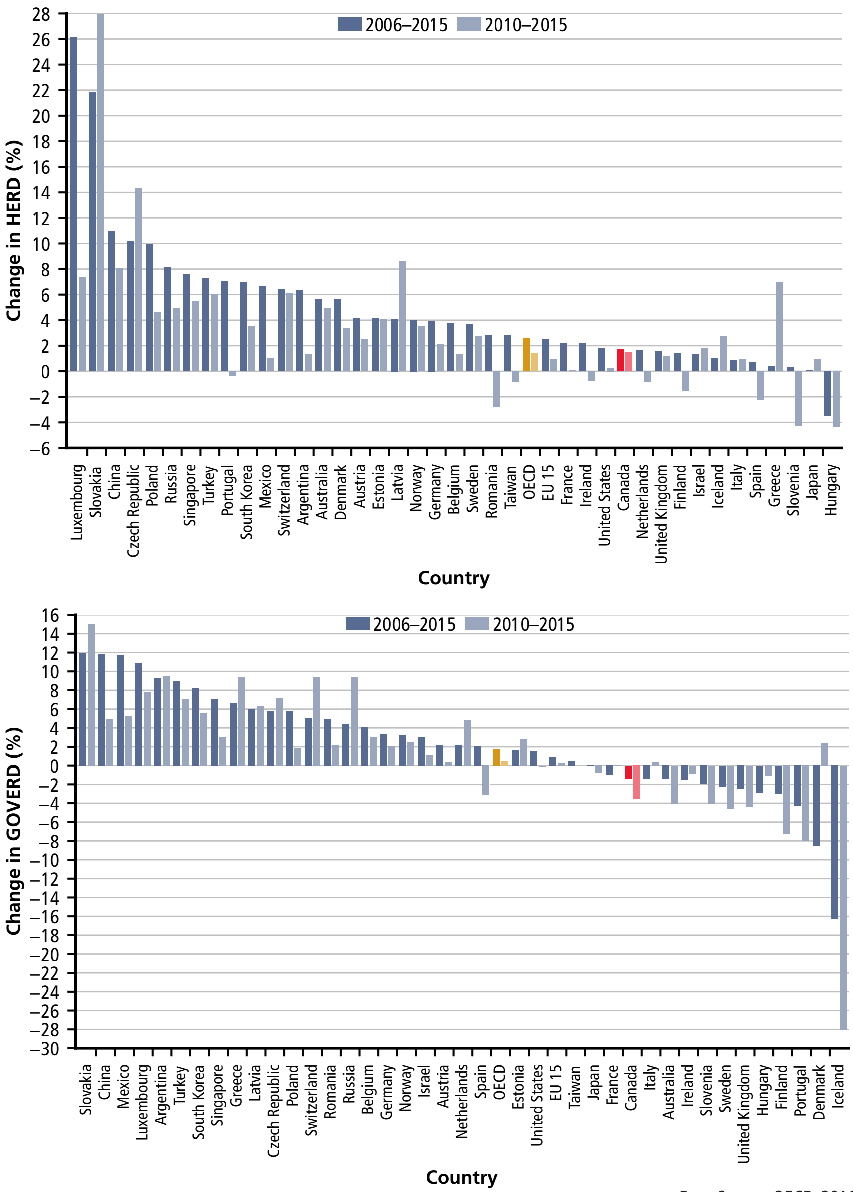
Percentage of HERD Financed by Industry, 2015

Industry accounts for a relatively higher share of R&D funding in the higher education sector in Canada, providing roughly 7.8% of total R&D funding for that sector in 2015. This is 1.6 percentage points higher than the average for OECD countries.

Recent trends in Canada have amplified these differences in R&D spending, with the most significant divergence occurring in the business sector. After taking inflation into account, R&D performed by firms in Canada increased by about 1% per year between 2010 and 2015, compared with an average increase of 3.5% in OECD countries (Figure 2.5). Although R&D investment grew in the Canadian higher education sector over the period, even here Canada's performance is lagging, with growth falling below the OECD average between 2006 and 2015. Canada's rank in higher education R&D investments as a share of GDP has also slipped in the past decade (OECD, 2016a).

Government-performed R&D (i.e., R&D performed in government laboratories and research facilities) declined between 2010 and 2015 (Figure 2.5). After factoring in inflation, federal and provincial R&D declined by 16% and 20%, respectively (StatCan, 2017h). Governments also fund R&D in other sectors. When looking at all government-funded R&D as a share of GDP, Canada still performs below the OECD average. Total government investment in R&D relative to the size of the economy dropped from 0.64% in 2010 to 0.56% in 2015 (OECD, 2016a).





Data Source: OECD, 2016a

Figure 2.5

Compound Annual Growth Rate (CAGR) in BERD, HERD, and GOVERD, 2006–2015

Adjusted for inflation, BERD has continued to decline in recent years, leaving Canada one of few countries in the OECD with negative R&D growth in the sector. HERD has increased modestly in comparison, though at a rate below the OECD average since 2006 based on constant 2010 U.S. dollars and purchasing power parity (PPP). Note that CAGR for BERD in Canada should be interpreted with caution given changes in Statistics Canada BERD data collection methodology between 2013 and 2014.

Declining government R&D and slowing R&D growth in the higher education sector are recent phenomena in Canada, partially reflecting fiscal constraints among federal and provincial governments following the 2008–2009 financial crisis.[10] Government investment in R&D across the OECD has declined modestly since 2010, as governments have faced economic headwinds with a slower than anticipated recovery and low economic and productivity growth (IMF, 2016). Low and declining industrial R&D investment in Canada as a proportion of GDP, however, is a long-standing trend.

Statistics Canada recently changed the survey methodology used to collect industrial R&D expenditures and related variables in Canada (the annual Research and Development in Canadian Industry or RDCI survey). Among other changes, this involved a transition from a census survey of roughly 2,000 respondents to a weighted sample survey of over 8,000 respondents, and a shift from a reporting period based on the calendar year to one based on the fiscal year ending March 31. The survey also now collects data on social sciences and humanities R&D spending by Canadian firms.

Data based on the new methodology were publicly released on April 20, 2017, covering R&D spending in 2014 and firm R&D intentions for 2015 and 2016. Statistics Canada has cautioned users against using the new data alongside the previous in analyses of trends over time. Use of the new methodology resulted in an 11.6% increase in the estimated R&D spending occurring in Canadian industry between 2013 and 2014, but it did not change the recent downward trend in expected R&D spending (Figure 2.6). This increase may indicate a jump in R&D spending among firms that year, or be an artefact of the change in methodology, or a combination of both. However, the scale of the increase seen in the 2014 data is not sufficient to reverse what appears to be a long-term pattern of underinvestment in R&D by Canadian firms relative to their OECD counterparts. The OECD data presented in figures 2.1, 2.2, 2.3, and 2.5 combine Statistics Canada from the old and new methodology. Trends in BERD and GERD in Canada should therefore be interpreted with caution. More details on these methodological changes are provided by Statistics Canada (StatCan, 2016c).

10 Note that most countries were affected by this financial crisis.

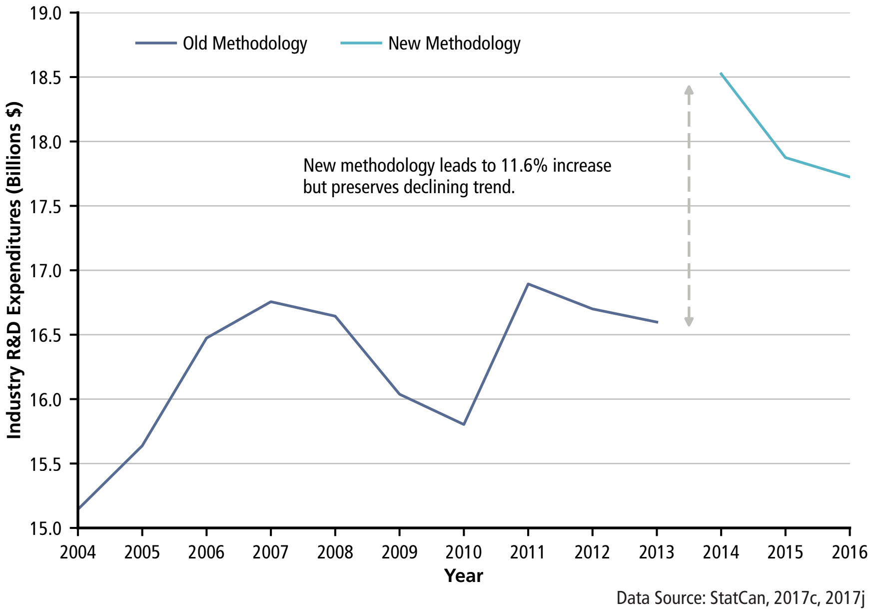


Figure 2.6

Industrial R&D Expenditures in Canada: Old Versus New Survey Methodology

The recent change in Statistics Canada's methodology for the Research and Development in Canadian Industry survey led to an 11.6% increase in estimated R&D spending in industry between 2013 and 2014. However, this change should be interpreted with caution as the overall downward trend has been preserved. R&D figures reported for 2015 and 2016 are for firm R&D spending *intentions*, as collected with the 2014 survey.

2.1.2 Cross-Sectoral Partnerships and Funding

Partnerships connect post-secondary institutions that undertake basic or applied research with external partners, usually firms but also not-for-profits, hospitals, government, and social agencies. Such linkages provide firms with access to innovative ideas, skills, and infrastructure found in academia. Partnerships also provide an opportunity for students and professors to train and work in an industrial environment. In the past decade, the Government of Canada has increased its emphasis on partnership programs. Both the 2007 and 2014 national S&T strategies highlighted the need to promote partnerships for the private sector and other research performers such as universities, colleges, polytechnics, and governments (GC, 2014). Canada is home to various organizations that promote partnership at the federal, provincial, and local level. It is beyond the scope of this report to examine partnership programs and federal funding programs in detail; however, the evolution of partnership funding at the Tri-Agency is illustrative of recent government priorities on the development of linkages between academia and the private sector.

At the federal level, the Tri-Agency administers partnership programs for post-secondary institutions (universities, colleges, and polytechnics) and private firms, government, and not-for-profit organizations. The Panel identified three key trends in Tri-Agency funding of partnership programs between 2010 and 2015:

- a modest increase in total funding, but a significant increase in the number of partner institutions (e.g., industry or government) involved;
- an increase in SSHRC and CIHR funding to partnership programs; and
- an increase in partnership funds dedicated to partnerships with colleges.

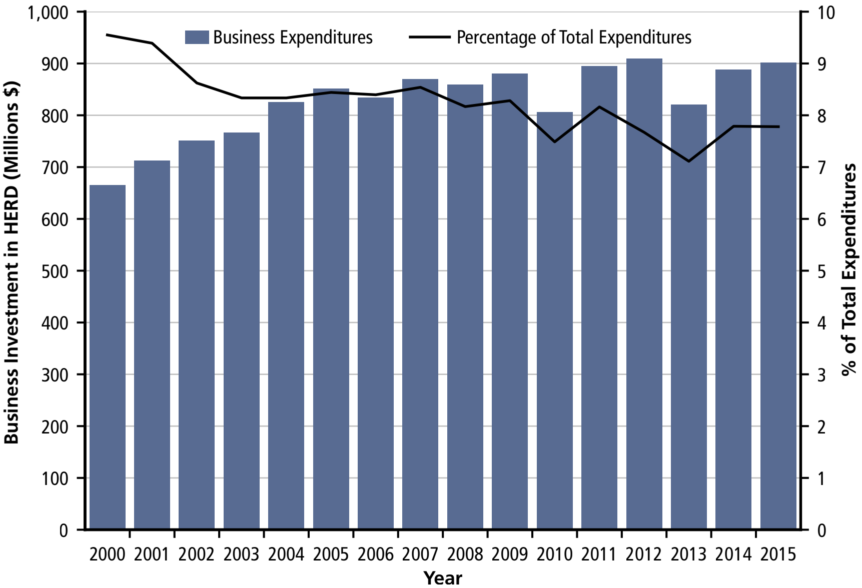
In 2015, the Tri-Agency invested about $410 million to support research partnerships: $330 million from NSERC, $50 million from SSHRC, and $30 million from CIHR. Corrected for inflation, the total Tri-Agency budget dedicated to partnerships increased by about 16% between 2010 and 2015. Most of this increase was driven by SSHRC (from $3 million to almost $50 million) and CIHR (approximately from $15 million to $30 million). Although the amount of dedicated NSERC funding did not significantly increase over the period, the number of partner institutions almost doubled, largely due to the creation and success of smaller partnership grants such as the Engage Grants. The drastic shift towards partnership grants at SSHRC indicates the influence of NSERC-type approaches to humanities and social science research, including more collaborative and team-oriented research. Finally, as a result of the 2007 and 2014 national S&T strategies, the amount of funding targeted at partnerships involving colleges increased significantly between 2010 and 2015. The majority of this increase was driven by the increase in NSERC's college partnership budget, which grew from $28 million in 2010 to $46 million in 2015 through the expansion of the College and Community Innovation (CCI) Program[11] (Box 2.1).

11 The information in this paragraph are Panel calculations based on data submitted by CIHR, and on NSERC and SSHRC Awards Data, available on the Government of Canada data portal at www.open.canada.ca. These data contain information licensed under the Open Government Licence — Canada. Partnerships are defined as follows: NSERC partnership: all programs labelled research partnership programs; SSHRC partnership: Partnership Development Grants and Partnership Grants; CIHR partnership: Collaborative Health Research Projects, Knowledge Synthesis Grant, Industry-Partnered Collaborative Research, Knowledge to Action, Partnerships for Health System Improvement, Proof of Principle Programs

Box 2.1
Applied Research Funding at Colleges and Polytechnics

On the R&D continuum, colleges and polytechnics have historically conducted applied research, primarily in partnership with local private-sector firms. They perform an applied research function as innovation intermediaries, linking to both private- and public-sector partners to enable innovation. This means acting as demand-driven innovation services organizations where industry and community partners can access skills and infrastructure: skills and expertise of college faculty and students, machinery and equipment, and markets and networks, with the objective of getting new products and services to market. Colleges also work with university partners and other public-sector actors. The CCI Program was initiated in 2007 to develop the college capacity to perform applied research with industry and community partners. The CCI Program is composed of a variety of grants that support the development of college capacity for applied research, starting with Innovation Enhancement grants (NSERC, 2015, 2017c). Colleges that have demonstrated the capacity to perform applied research for particular industries in their areas are awarded renewable funding through the Technology Access Centre program. Technology Access Centres (TACs) have been developed based on the successful *Centres collégiaux de transfert de technologie* (CCTT) in Quebec. Like the CCTT, TACs focus on providing applied research services and helping private-sector partners to develop or refine new products more quickly. The Industrial Research Chairs for Colleges program run by NSERC supports individual faculty members to work with companies in their regions. Finally, the Panel noted few available longitudinal data that demonstrate the contributions that colleges make to industrial R&D.

Partnership programs have increased the number of partnerships between businesses and post-secondary institutions and fostered new connections among industry and academia. However, these programs have, as of yet, had a limited impact on business R&D investment at the national level. Taking inflation into account, the level of business investment in R&D undertaken in the higher education sector has been relatively constant over the past decade (at around $800 million in constant 2007 dollars). As a share of business expenditures on R&D, this is high by OECD standards. However, this ratio has gradually declined in the past decade. There is no indication that Tri-Agency partnership programs led to an overall increase in business investment in higher education R&D in Canada prior to 2015, though data for subsequent years may eventually reveal such an impact. Some of these grants also require in-kind contributions to research activities that are not captured in R&D expenditure data.



Data Source: StatCan, 2017h

Figure 2.7

Business Investment in Higher Education R&D in Canada, 2000–2015

The figure shows the amount (in constant 2007 dollars) of business funding for R&D awarded to the higher education sector, as well as the share of business-funded R&D to all R&D in the sector. As seen here, there has not been a substantial increase in this funding since 2007, and it has gradually declined as a share of the total.

According to an NSERC survey, three out of four companies plan further partnered research at the end of a project, indicating that these programs are successful at encouraging firms to work with universities and colleges (NSERC, nd-a). In addition, partnership programs are a key element in training students involved in research for the challenges specific to the private sector. Around 10,000 students train through NSERC partnership programs each year in industry, and one in three companies hire students involved in partnership programs (NSERC, nd-b). Mitacs, a not-for-profit organization founded in 1999 as a Canadian Network Centre of Excellence, has also helped connect companies and not-for-profit organizations with graduate students and postdoctoral fellows. In 2015/16, Mitacs placed 3,657 interns in positions in industry (Mitacs, 2016).

The Panel recognizes that partnerships are controversial in some segments of the post-secondary community, which might view them as taking funding away from basic research. Systematic measurement of the outputs and outcomes of these partnerships may help identify successful programs and outcomes, such as graduates employed with research partners, and the likelihood to engage in other research activities at the firm level. On that point, the Panel notes that NSERC is making efforts to track the output and outcomes of some of their partnership programs (such as NSERC, nd-a). Nonetheless, the trend towards increased collaboration and partnerships between industry and higher education institutions combined with flat business expenditures on R&D in the higher education sector remains a puzzling anomaly that is not fully accounted for in existing data or research available to the Panel.

2.2 EDUCATION AND R&D PERSONNEL

Science is a human enterprise. To advance the frontiers of R&D, researchers must participate at the highest levels, which in turn demands an education system capable of training the next generation of researchers as well as universities that can attract researchers and students from around the world. Canada has traditionally excelled in this domain, and continues to do so, according to the latest data from the OECD and Statistics Canada.

2.2.1 Education and Teaching

Canada's population continues to be among the best educated in the world, having both a solid educational foundation in science and mathematics, and high levels of educational attainment overall. At the primary and secondary level, Canadian students perform well in international assessments and results are mainly consistent across the country. According to the latest results from the OECD's Programme for International Student Assessment (PISA), Canada ranks third in the OECD and fourth out of all countries in an assessment of science knowledge and skills among 15-year-olds. Canadian students also excel in the mathematics assessment, ranking 5th in the OECD and 10th among all countries. Canada has consistently performed well since these assessments began in 2003; however, its competitiveness compared with other leading countries has declined over time, particularly in mathematics (OECD, 2016e).

Canada invests more in post-secondary education than most countries, with the sixth highest level of expenditure per student per year among OECD countries (OECD, 2016e). Canada also has one of the highest levels of educational attainment of all countries, with over 55% of the population aged 25 to 64 completing some post-secondary (i.e., university or college) education (Figure 2.8). However, Japan and South Korea have now surpassed Canada in the share of young adults (aged 25 to 34) with post-secondary education, and the proportion of the Canadian population holding master's or doctoral degrees is lower than the OECD average (OECD, 2016e).

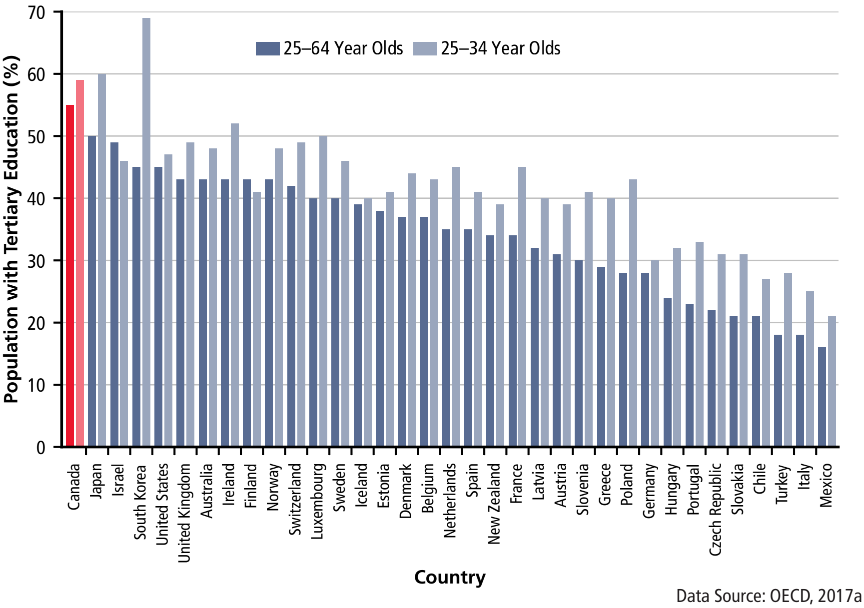


Figure 2.8

Percentage of the Population with Post-Secondary Education, 2015

Canada has one of the highest levels of educational attainment in the OECD among the adult population, with over 55% of people aged 25 to 64 having some post-secondary education (defined as tertiary in OECD data), and 59% of those aged 25 to 34.

Canada continues to have a growing population of students graduating from its post-secondary education system, and now produces over 400,000 post-secondary graduates annually (StatCan, 2017e). However, the growth rates of different degree programs vary. The number of graduates with Bachelor's degrees or their equivalent grew by 7% between 2006 and 2010 and by 9% between 2010 and 2015. In comparison, the number of graduates at the Master's level in Canada increased by 21% and 17% respectively for these two periods, while the number of Doctoral graduates increased by 34% and 18%. Canada also is attracting increasing numbers of international students, particularly at the master's and doctoral level. The proportion of international students graduating from Canadian universities increased by almost 4 percentage points in five years, from 7.0% in 2010 to 10.5% in 2015 (StatCan, 2016b), a trend which appears to be accelerating following the 2016 U.S. elections (Chiose, 2017).

Table 2.1
Number and Growth Rate of Postsecondary Graduates in Canada by Program Type

Program Type	2011	2012	2013	2014	2015	Change 2006–2010 (%)	Change 2011–2015 (%)
Career, technical or professional training program	161,418	166,245	170,451	174,771	169,344	20	5
Bachelor's or equivalent	183,639	188,379	197,262	200,403	200,652	7	9
Master's or equivalent	49,935	52,296	54,789	55,158	58,659	21	17
Doctoral or equivalent	6,258	6,477	7,140	7,086	7,407	34	18

Data Source: StatCan 2017e

This table shows the number of postsecondary graduates in Canada who have successfully completed their degree. Program types are based on the International Standard Classification of Education (ISCED), except for "career, technical or professional training programs," which combines ISCED program types for post-secondary non-tertiary education and short-cycle tertiary education. These programs are offered primarily, though not exclusively, by colleges in Canada. Similarly Bachelor's degrees or their equivalent are granted primarily by universities in Canada, though colleges grant a small portion as well.

Just over 20% of the college and university degrees awarded in Canada are in the sciences or engineering; this share is near the OECD average (OECD, 2016e). While the share has increased modestly in Canada since 2004, most OECD countries have experienced declining enrolment in science and engineering programs. At the doctoral level, the number of science and engineering degrees granted has increased significantly in Canada in recent years, more than doubling between 2004 and 2012, from about 1,400 to 3,300 (OECD, 2016e). Among OECD countries, Canada's production of doctoral degrees per capita across all fields of study is relatively low, though not far below that of the United States (Figure 2.9). However, its performance has improved considerably on this measure in recent years due to an increase in the number of science and engineering doctoral degrees granted (STIC, 2015).

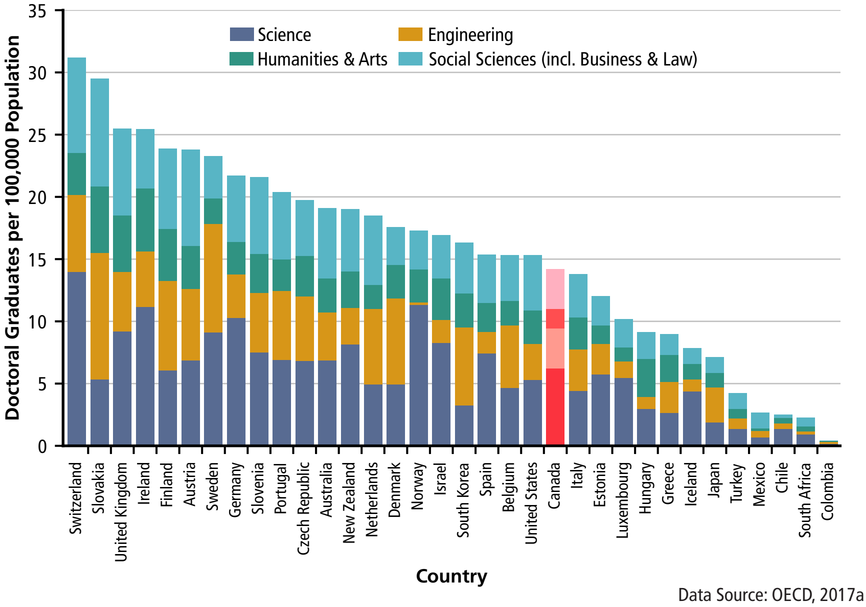


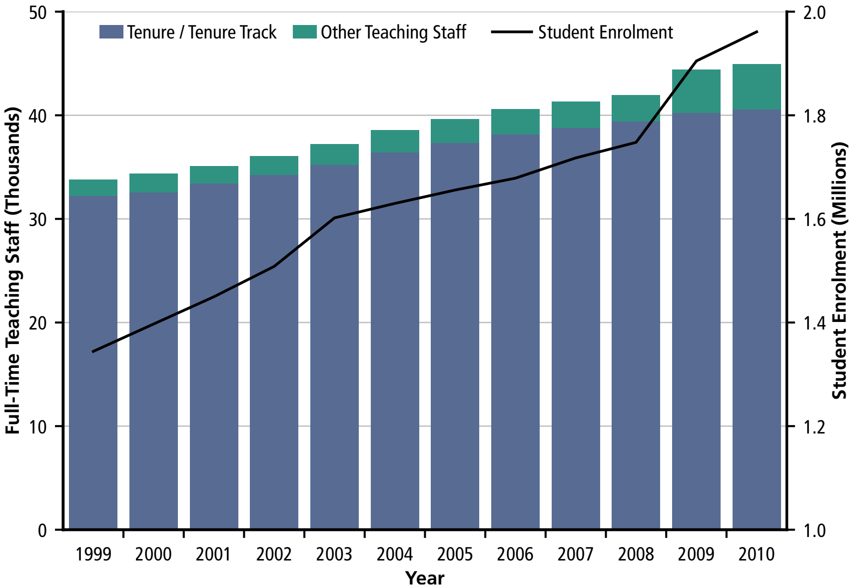
Figure 2.9

Doctoral Graduates by Field per 100,000 Population, 2012

On a per capita basis, Canada's production of doctoral degrees remains relatively low compared with other countries. Data for Australia are for 2011.

Universities are moving towards a model where students are increasingly taught by non-tenure teaching staff and sessional faculty. Between 1999 and 2010, the number of non-tenure teaching staff increased by 174%, with a particularly sharp increase between 2008 and 2009, whereas the number of tenured professors only increased by 26% (Figure 2.10).

About 40% of all PhD graduates in Canada work in the post-secondary education sector and only 20% of all PhD graduates end up as full-time professors. Many PhDs find work in the private sector. However, the rate of employment for PhD students is higher than that for master's and bachelor's degree holders and their career satisfaction is high (Edge & Munro, 2015; Advisory Panel for the Review of Federal Support for Fundamental Science, 2017). The fact that many PhDs are employed in industry is likely beneficial for Canada's capacity for R&D and innovation in the private sector. The design of these programs should take into account the diversity of employment trajectories followed by recent graduates.



Data Source: StatCan, 2012d, 2017p

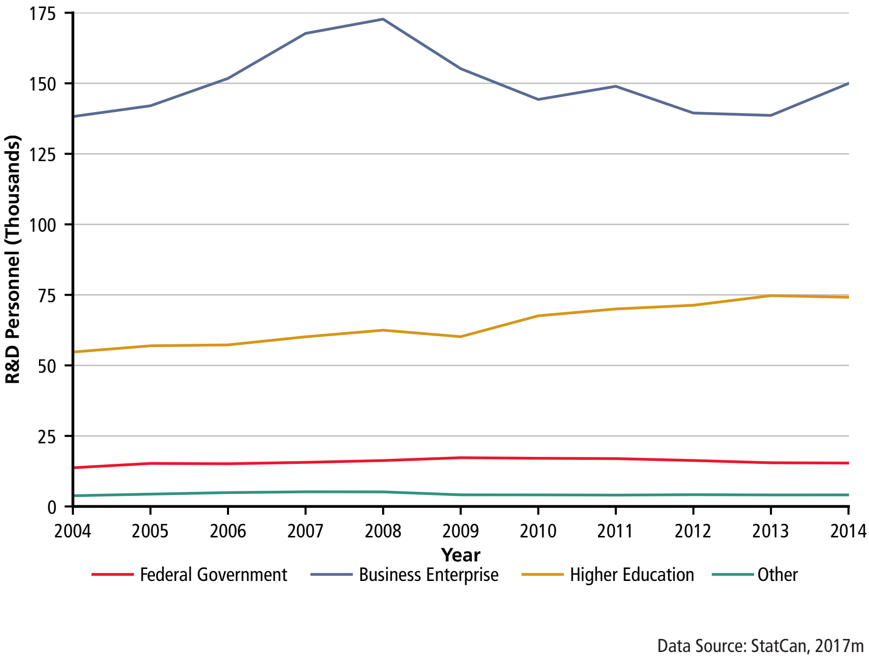
Figure 2.10

Changes in Full-Time Teaching Staff at Canadian Universities, 1999–2010

"Tenured or tenure-track faculty" include full professors, associate professors, and assistant professors. The category "Other Teaching Staff" contains ranks or levels below assistant professors (including lecturers and instructors) and other ranks (including ungraded staff). Years are academic years. For example, year 2000 corresponds to the 2000/01 student academic year. Total student enrolment follows the International Standard Classification of Education. Note that Full-Time Teaching Staff data are not currently available after the year 2010.

2.2.2 Personnel

According to Statistics Canada, between 2004 and 2014, the total number of researchers in Canada grew by over 30,000 (StatCan, 2017m). However, this hides disparities across performing sectors. The number of industrial R&D personnel decreased significantly after the 2008 financial crisis (by 20% between 2008 and 2013) whereas the number of higher education R&D personnel continued to increase. However, the latest data suggest that the number of R&D personnel in industry may now be starting to recover (Figure 2.11).



Data Source: StatCan, 2017m

Figure 2.11

Personnel Engaged in R&D in Canada, by Performing Sector, 2004–2014

In Canada, most R&D personnel work for the private sector (over 60% in 2014). Although the number of employees remained stable in the private sector, it increased by about 35% in higher education between 2004 and 2014. "Other" includes provincial government and private not-for-profit. Personnel counts are in full-time equivalent.

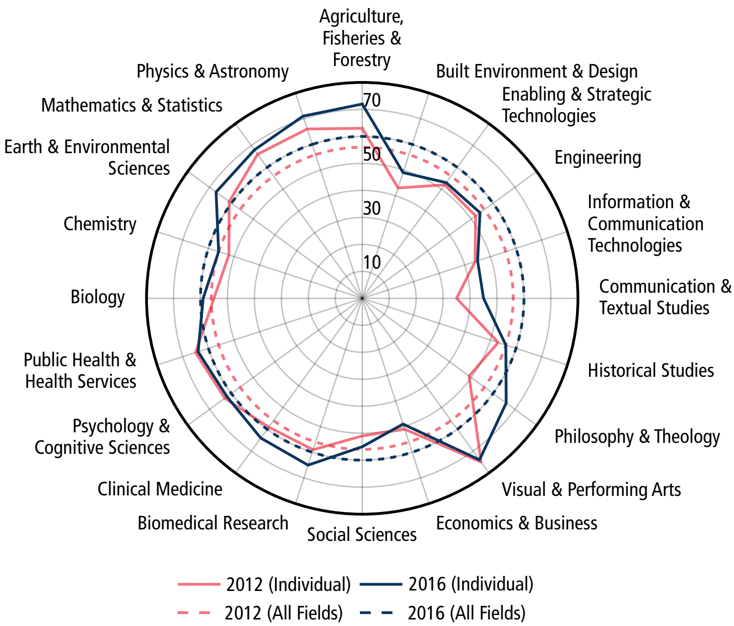
On a per capita basis, in 2014, the number of full-time researchers in Canada was similar to countries such as France, Germany, United Kingdom, and United States (at about 4,500 researchers per million inhabitants) (OECD, 2016f).[12] This rate is much higher than that of China (about 1,100 researchers per million inhabitants) and much lower than that of Sweden (about 6,900 researchers).

12 According to the OECD's *Frascati Manual* (OECD, 2015b), researchers are "professionals engaged in the conception or creation of new knowledge. They conduct research and improve or develop concepts, theories, models, techniques instrumentation, software or operational methods."

2.3 R&D INFRASTRUCTURE

State-of-the-art research programs, facilities, and infrastructure are essential for participation in world-leading research in most fields. In Canada, the Canada Foundation for Innovation (CFI), a not-for-profit, arm's length institution founded in 1997, is the main funding agency that invests in the research infrastructure of post-secondary institutions, research hospitals, and not-for-profit research organizations. Since its funding model is based on a third-party contribution agreement, over half of the cost is covered by partners such as provincial governments, universities, businesses, and charities (Advisory Panel for the Review of Federal Support for Fundamental Science, 2017). Between 1998 and 2016, CFI awarded 9,464 projects for a total of about $5.5 billion. The greater proportion of funding was awarded to health sciences (41%), applied sciences (25%), and natural sciences (27%). The remainder was attributed to economic and social sciences and arts and humanities (CFI, personal communication). The federal government also maintains an extensive range of research facilities through National Research Council Canada (NRC), and through programs and infrastructure managed by other federal departments.

Data from two CCA surveys of top-cited researchers from around the world (from 2012 and 2016; Sections 1.3.2 and 3.1.2) can help inform an assessment of Canada's research programs or infrastructure by field. In 2012, just over half (56%) of researchers surveyed felt that Canada had world-leading research programs or infrastructure in their fields. In 2016, that share increased to 60%. Fields where at least two-thirds of respondents indicated that this was the case include: Visual and Performing Arts; Agriculture, Fisheries and Forestry; Physics and Astronomy; Mathematics and Statistics; Earth and Environmental Sciences; and Philosophy and Theology. Between the two survey years, most fields saw positive changes in response to this question. Only four fields had declines, none of which exceeded two percentage points. The fields with the largest improvements were Philosophy and Theology; Communication and Textual Studies; and Agriculture, Fisheries and Forestry (Figure 2.12).



Data Source: Panel calculations based on 2012 and 2016 surveys of top-cited researchers

Figure 2.12

Percentage of Survey Respondents Indicating that Canada Has World-Leading Research Programs or Infrastructure by Research Field, 2012 and 2016

More than half of the top-cited researchers surveyed indicated that Canada had world-leading research in their fields of study, and this percentage has increased in most fields since 2012. The surveys were developed and commissioned by the CCA. Survey question: In your opinion, does Canada have particular infrastructure or research programs in your area of expertise that are of worldwide importance?

2.4 CONCLUSION

For two of the three pillars underlying research performance, the evidence reviewed by the Panel is encouraging. Survey evidence suggests that Canada is home to world-leading research infrastructure and programs in many fields, and its international reputation with respect to these assets is improving. Most measures of research talent suggest Canada remains competitive on the world stage, with a highly educated population, a high-performing educational system, and a modestly growing number of researchers per capita. The only significant point of concern is the declining number of R&D personnel employed in industry, which is directly related to the overall decline in business investment in R&D. Federal government support for partnership programs is also increasing companies' access to research talent and providing PhD students with employment and training opportunities in an industrial setting.

For the final pillar, however, the data warrant significant concerns. Canada's overall level of investment in R&D is not keeping pace with that of other countries. This is especially true in the business sector, but levels of R&D spending in government and higher education are also increasingly falling behind those of OECD peers. Like other previous expert panels and committees (STIC, 2015; Advisory Panel for the Review of Federal Support for Fundamental Science, 2017), this Panel finds Canada's pattern of relative underinvestment in R&D to be alarming. If current R&D investment trends continue, they could significantly erode Canada's ability to participate in cutting-edge research in the future.

3

Research Output and Impact

- Canada’s Research Productivity
- Canada’s Research Performers
- Canada’s International Standing by Field of Study
- Canada’s Research Strengths
- Enabling and Strategic Technologies
- Data Limitations
- Conclusion

3 Research Output and Impact

Key Findings

Canada's research output has kept pace with other developed countries in recent years.

- Canada produces 3.8% of the world's research publications, but fell from seventh to ninth place in publication output between 2003–2008 and 2009–2014.
- Publication output in Canada grew by 26% between 2003 and 2014, above the rate of many developed countries including the United States. Federal government research output, however, dropped significantly between 2009 and 2014.

Canadian research is comparatively less specialized and less esteemed in the core fields of the natural sciences and engineering.

- Canada has comparatively high levels of research output in Psychology and Cognitive Sciences, Public Health and Health Services, Philosophy and Theology, Earth and Environmental Sciences, and Visual and Performing Arts.
- Canada has disproportionately low research output in Chemistry, Physics and Astronomy, Enabling and Strategic Technologies, Engineering, and Mathematics and Statistics.

Canada is maintaining its international standing in overall research impact, but evidence suggests a minor erosion of research competitiveness in many fields.

- In 2009–2014 Canada's global rank by ARC remained unchanged at sixth place from the CCA's 2012 S&T assessment.
- Top-cited international researchers ranked Canada fourth in the world in 2016, with 36% ranking it among the top five countries in their field.
- With ARC scores above the world average for all fields, Canada ranks among the top five countries in Psychology and Cognitive Sciences, Clinical Medicine, Physics and Astronomy, Historical Studies, and Visual and Performing Arts.
- Small declines in ARC rankings occurred in the majority of fields between 2003–2008 and 2009–2014.

Based on bibliometric indicators of magnitude, impact, and growth, Canada's top-performing fields are Visual and Performing Arts, Psychology and Cognitive Sciences, Clinical Medicine, Public Health and Health Services, and Philosophy and Theology.

- Ten of the top 20 subfields are in the health sciences while the bottom 20 feature several Engineering and Enabling and Strategic Technologies subfields; and
- Significant variation exists within fields, for example Visual and Performing Arts contains both the highest and lowest ranked subfields.

continued on next page

Canada is not a world leader in most enabling and strategic technologies.

- Canada has lost ground to other countries in areas where it played a seminal role in early research, such as Artificial Intelligence and Regenerative Medicine, though there remains substantial research capacity in these areas.

This chapter examines the output and impact of Canadian research activities using bibliometric indicators and results from a survey of top-cited researchers around the world. It also provides an assessment of Canada's current research strengths based on three underlying dimensions: *magnitude* (the extent of Canada's research output relative to the rest of the world), *impact* (the influence of research on later publications as reflected in citations), and *growth* (the change in Canada's research output over time relative to the world average).

To assess trends over time, bibliometric indicators were calculated for two periods: 2003–2008 and 2009–2014. Data were extracted from Elsevier's Scopus database and include peer-reviewed journal articles, conference papers, and a limited set of academic books and book chapters. Citation-based indicators are used as a measure of the impact of Canadian research, though the validity and usefulness of these indicators vary by field. Methodological limitations associated with the bibliometric analysis and the survey are discussed in Section 3.6. Descriptions of key indicators are provided in Table 3.1 and the Glossary.[13]

Table 3.1

Selected Bibliometric Indicators Used in this Report

Indicator	Description
Number of Publications	Number of publications measures the publication count for a given entity such as a country, a province, or a research field. Publication counts can be presented in whole and fractional counts. With whole counting, each publication is counted once for each unit with a participating author. For example, if a publication is co-authored by two researchers from different countries, the publication will be counted once for each country. With fractional counting, each co-author (and associated entity) is credited with a fraction of a publication corresponding to the number of authors. In the preceding example, each researcher (and country) would be allotted one-half of a publication. Unless otherwise indicated, the counts presented in this report are based on whole counts. However, some metrics use fractional counts.

continued on next page

13 A complete description of the bibliometric methodology, including the details on the construction of each indicator, is available upon request.

Indicator	Description
Specialization Index (SI)	This indicator is a measure of the relative research intensity for an entity in a specific field of research. An SI score greater than 1.0 means that more publications were published in a given field or subfield than would be expected based on world averages. For example, if publications in Physics and Astronomy account for 10% of a country's total publications, but only 5% of total world publications, that country would have an SI score of 2.0 in that field. An SI score below 1.0 means that less research is produced than expected based on world averages.
Growth Index (GI) and Growth Rate (GR)	GI score measures the growth of publications between two periods of time (2003–2008 and 2009–2014 in this report) relative to the growth of a reference entity (e.g., the world) for the same period of time. For example, if Canada's GI is above 1.0 for a specific field or subfield, it means that Canada's publication output in that field or subfield is growing faster than the world average. The GR indicator simply corresponds to the percentage change in total publication output between the two periods; a GR score of 1.37, for example, indicates that output increased by 37% between the two periods.
Collaboration Index (CI)	Based on publication co-authorships, the CI indicator measures the level of collaboration of a given entity with another entity in the context of the entity's total publications (countries producing more publications tend to collaborate less internationally, given their increased potential for internal collaboration). A collaboration score over 1.0 means that the entity collaborates more than expected given its total publication output.
Average Relative Citations (ARC)	This indicator measures the impact of publications produced by a given entity as reflected in citations. An ARC score over 1.0 indicates that the entity publishes publications that are more highly cited than the world average. ARC scores are normalized by publication type, year, and field of research. ARC scores (along with other measures of impact) are less reliable for fields or entities producing low numbers of publications, as the score can be driven by outliers.
Median Relative Citations (MRC)	The MRC is similar to the ARC and is also a measure of research impact based on field-normalized citations. However, the MRC is calculated with reference to the median score rather than to the average. It is arguably a better measure of the central tendency in most areas of research given that citation distributions tend to be skewed, with a small number of publications attracting large numbers of citations.
Highly Cited Publications (HCP1%)	HCP1% is a measure of research impact based on the upper tail of the distribution of normalized citation counts. The top-cited 1% of publications are identified by field or subfield for a given period. A value above 1.0 indicates that the entity has more highly cited publications than expected based on its share of all publications in that field or subfield. For example, if Paleontology in Canada represented 1% of global publications but 2% of highly cited publications, its HCP1% value would be 2.0.

3.1 CANADA'S RESEARCH PRODUCTIVITY

Canada produces 3.8% of the world's research output[14] and continues to rank in the top 10 countries in total output of research publications, but that standing is eroding. In the 2012 S&T report, Canada ranked seventh in the 2005–2010 period, with roughly 395,000 scientific publications. Although Canadian researchers[15] produced even more publications in the 2009–2014 period (496,696), India and Italy have overtaken Canada to reach the seventh and eighth positions, respectively. Canada has fallen to ninth place, but the distance separating Canada from Italy is negligible, at approximately 2,300 publications. The United States continues to lead in number of publications, but the gap with China is rapidly narrowing[16] (Table 3.2).

Measuring output of publications relative to a country's population, Canada ranks fifth, producing about 14 publications per 1,000 inhabitants in the 2009–2014 period (Table A.2 in the appendix). This indicator shows China's rank to be lower on a per capita basis; however, this could also indicate China's potential for considerable future growth. For countries such as Switzerland, the high publication output per capita reflects a high rate of international collaboration and the presence of major scientific research facilities such as CERN (European Organization for Nuclear Research), which are associated with global networks of researchers.

To estimate research efficiency, publication output can also be normalized by number of researchers. From 2009 to 2013, Canada produced on average about 52 publications per 100 researchers while the United States produced 41 publications.[17] Italy ranks first with 76 publications per 100 researchers and Russia last with 9 publications.

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14 Calculated from whole counts. As publications with co-authors in different countries are counted for each country, this should be interpreted as the share of world publications that Canada participated in rather than as an exclusive share.

15 *Canadian researcher* in this bibliometric study refers to a researcher based at a Canadian institution, and not to the researcher's nationality or citizenship.

16 These data likely understate growth in publication output in China given that journal coverage in Scopus is biased towards English-language journals (Rousseau, 2015). Publication data for China may also be misleading in some cases due to relatively widespread research misconduct and fraud (Hvistendahl, 2013), though the impact of such activity on total publications and related trends is unknown.

17 Publication output by researchers (full-time equivalent) and HERD expenditure were calculated for the top 20 countries by output for the 2009–2013 period except for India, Brazil, Iran, Australia, and Switzerland (where data were not available or only partially available). Full-time equivalents for researchers and HERD expenditures were retrieved from the OECD (OECD, 2016a).

Table 3.2

Top 20 Countries by Number of Scientific Publications Produced and Other Key Indicators, 2003–2008, 2009–2014, and 2003–2014

Rank (2009–2014)	Country	Number of Publications		Share of World Publications (%)		CI		GI	GR
		2009–2014	2003–2008	2009–2014	2003–2008	2009–2014	2003–2008	2003–2014	
1	United States	3,136,910	2,633,098	24.3	29.2	1.00	0.89	0.80	1.15
2	China*	2,600,858	1,207,471	20.1	13.4	0.48	0.46	1.50	2.15
3	United Kingdom	869,569	682,941	6.7	7.6	1.39	1.26	0.83	1.19
4	Germany	837,314	651,436	6.5	7.2	1.34	1.29	0.86	1.23
5	Japan	728,582	685,686	5.6	7.6	0.68	0.65	0.72	1.04
6	France	611,138	479,262	4.7	5.3	1.35	1.27	0.84	1.21
7	India	545,655	246,898	4.2	2.7	0.46	0.51	1.56	2.24
8	Italy	499,039	364,427	3.9	4.0	1.13	1.06	0.92	1.31
9	Canada	496,696	377,779	3.8	4.2	1.26	1.20	0.88	1.26
10	Spain	431,204	281,290	3.3	3.1	1.14	1.01	1.01	1.46
11	Australia	398,375	252,189	3.1	2.8	1.22	1.09	1.03	1.49
12	South Korea	388,387	234,694	3.0	2.6	0.69	0.71	1.15	1.64
13	Brazil	321,960	177,451	2.5	2.0	0.65	0.71	1.28	1.84
14	Netherlands	280,459	201,344	2.2	2.2	1.37	1.28	0.91	1.30
15	Russia	256,825	208,439	2.0	2.3	0.74	0.91	0.89	1.27
16	Iran	211,646	63,321	1.6	0.7	0.46	0.49	2.37	3.41
17	Switzerland	207,018	146,791	1.6	1.6	1.59	1.53	0.91	1.31
18	Turkey	199,421	122,841	1.5	1.4	0.45	0.42	1.11	1.60
19	Poland	194,570	140,014	1.5	1.6	0.72	0.81	0.98	1.41
20	Sweden	180,825	137,728	1.4	1.5	1.38	1.28	0.83	1.19
	World	12,935,138	9,006,984	100	100			1.00	1.44

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

The share of world publication is calculated from whole counts. Each author receives full credit for the publication regardless of the number of authors. Using fractional publication counts, Canada's share of world publications would be 2.8%. Countries are ranked by the total number of publications for the 2009–2014 period. Full counts show greater output for countries with a higher propensity to collaborate and/or with more research in fields with a high propensity to collaborate. Canada ranks ninth both in full and fractional counts.

*Note that Science-Metrix combines by default Taiwanese and Chinese publications.

When ranked by GDP, an indicator of the size of the national economy, Canada is 12th in overall output. Iran ranks first by this measure, producing over 70 publications per billion dollars of GDP; in contrast Canada produces fewer than 50 publications (Table A.3 in the appendix). Although GDP may indicate a country's capacity to invest in research, normalization by Higher Education Expenditures on R&D (HERD) may be more appropriate as a measure of the productivity of research investments. Canada publishes about 9 publications per $1 million investment in HERD; Japan has the lowest ratio with 6 publications and China the highest with 22 publications.[18]

Growth in research output, as estimated by number of publications, varies considerably for the 20 top countries. Brazil, China, India, Iran, and South Korea have had the most significant increases in publication output over the last 10 years. In particular, the dramatic increase in China's output means that it is closing the gap with the United States. In 2014, China's output was 95% of that of the United States, compared with 26% in 2003.

Table 3.2 shows the Growth Index (GI), a measure of the rate at which the research output for a given country changed between 2003 and 2014, normalized by the world growth rate. If a country's growth in research output is higher than the world average, the GI score is greater than 1.0. For example, between 2003 and 2014, China's GI score was 1.50 (i.e., 50% greater than the world average) compared with 0.88 and 0.80 for Canada and the United States, respectively. Note that the dramatic increase in publication production of emerging economies such as China and India has had a negative impact on Canada's rank and GI score (see CCA, 2016).

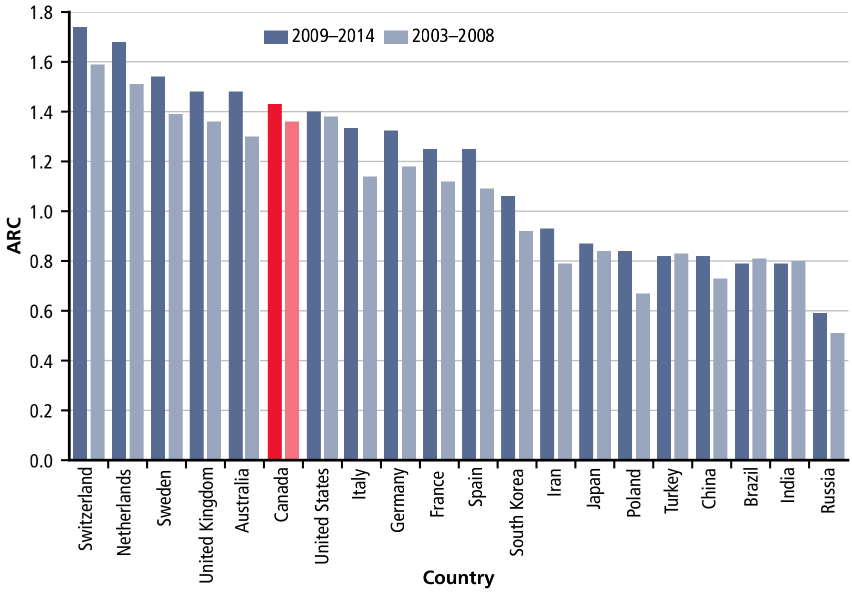
3.1.1 Research Impact

Canadian researchers continue to produce high-impact publications as reflected by citation rates. In the 2012 S&T report, Canada ranked sixth based on the Average Relative Citations (ARC) score for publications with at least one Canadian author. In the latest data (Figure 3.1), Canada maintained its rank for the 2009–2014 period as did the top three countries.[19] However, the United States fell from fourth to seventh place and Australia rose from seventh to fourth, and is now tied with the United Kingdom.

18 Note that such a measure may favour Canada because a high proportion of Canada's research is undertaken in higher education (see Chapter 2).

19 Note that the difference in the ARC scores of Canada and the United States is marginal.

The impact of Canada's research continues to improve relative to the world average: its ARC score increased from 1.36 in the 2003–2008 period to 1.43 in 2009–2014 (Figure 3.1). However, ARC scores for most advanced economies also increased between the two periods. The Median Relative Citations (MRC) indicator shows a similar pattern. With an MRC score of 1.50, Canada is tied in fifth place with the United Kingdom and United States. In comparison, some countries with high GI scores, such as China, Brazil, India, and Iran, have comparatively low citation levels. The Highly Cited Publications (HCP1%) indicator for each country is also shown in Table 3.3, corresponding to the extent of over- or under-representation in the top 1% of publications. Canada again ranks sixth in the world by this measure for the 2009–2014 period, tying with the United States.[20]



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

Figure 3.1

ARC Scores for Top 20 Countries by Number of Publications, 2003–2008 and 2009–2014

Countries are ranked by ARC score for the 2009–2014 period.

20 See CCA (2016) for a discussion on the differences in the ARC, MRC, and HCP1% metrics.

Table 3.3

Key Indicators of Research Impact for Top 20 Countries by Research Output, 2003–2008 and 2009–2014

Country	2009–2014			2003–2008		
	ARC	MRC	HCP1%	ARC	MRC	HCP1%
Switzerland	1.74	1.92	2.72	1.59	1.67	2.22
Netherlands	1.68	2.00	2.49	1.51	1.75	1.98
Sweden	1.54	1.67	2.06	1.39	1.60	1.63
Australia	1.48	1.56	2.01	1.30	1.47	1.51
United Kingdom	1.48	1.50	1.99	1.36	1.50	1.67
Canada	1.43	1.50	1.85	1.36	1.50	1.57
United States	1.40	1.50	1.85	1.38	1.47	1.76
Italy	1.34	1.43	1.57	1.14	1.20	1.16
Germany	1.32	1.33	1.68	1.18	1.20	1.30
France	1.25	1.22	1.52	1.12	1.08	1.19
Spain	1.25	1.25	1.44	1.09	1.13	1.06
South Korea	1.06	1.00	0.99	0.92	1.00	0.77
Iran	0.93	1.00	0.74	0.79	1.00	0.54
Japan	0.87	1.00	0.73	0.84	0.93	0.65
Poland	0.84	0.75	0.79	0.67	0.57	0.51
China	0.82	0.82	0.75	0.73	0.67	0.61
Turkey	0.82	0.75	0.73	0.83	0.83	0.60
India	0.79	0.67	0.58	0.80	0.79	0.63
Brazil	0.79	0.80	0.60	0.81	0.90	0.53
Russia	0.59	0.33	0.49	0.51	0.33	0.37

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

Countries are ranked by ARC for the 2009–2014 period. Only the top 20 countries by total publications are used in this ranking. Including all countries would change this ranking.

3.1.2 International Perceptions of Canadian Research

As with the 2012 S&T report, the CCA commissioned a survey of top-cited researchers' perceptions of Canada's research strength in their field or subfield relative to that of other countries (Section 1.3.2). Researchers were asked to identify the top five countries in their field and subfield of expertise: 36% of respondents (compared with 37% in the 2012 survey) from across all fields of research rated Canada in the top five countries in their field (Figure B.1 and Table B.1 in the appendix). Canada ranks fourth out of all countries, behind the United States, United Kingdom, and Germany, and ahead of France. This represents a change of about 1 percentage point from the overall results of the 2012 S&T survey. There was a 4 percentage point decrease in how often France is ranked among the top five countries; the ordering of the top five countries, however, remains the same.

When asked to rate Canada's research strength among other advanced countries in their field of expertise, 72% (4,005) of respondents rated Canadian research as "strong" (corresponding to a score of 5 or higher on a 7-point scale) compared with 68% in the 2012 S&T survey (Table 3.4).[21]

Table 3.4

Breakdown of Survey Respondent Ratings for Canada

Rank	Description	Number of responses	Percentage
7	Widely acknowledged to be world-leading (very strong).	824	14.9
6	Above world standards but falls short of the highest standards.	1,746	31.5
5	Generally above world standards (strong).	1,435	25.9
4	At the level of world standards (about the same).	1,089	19.6
3	Below world standards (weak).	296	5.3
2	Generally acknowledged to be below world standards.	52	0.9
1	Widely acknowledged to be below world standards (very weak).	22	0.4
	Don't know.	83	1.5

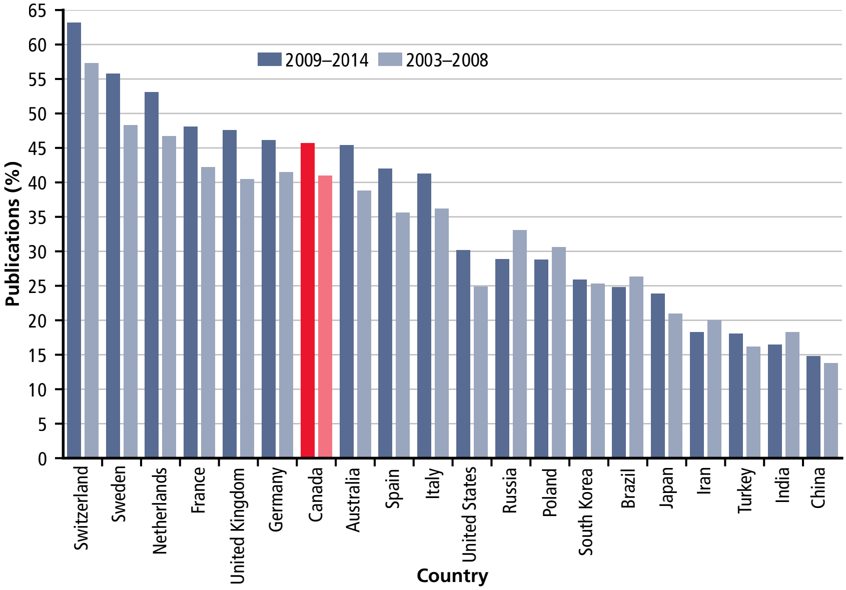
Survey question: What is your opinion of Canada's research strength in your area of expertise? Please compare with other advanced countries. Please use the following scale when rating Canada's relative strength.

3.1.3 Global Research Collaboration

Research is increasingly collaborative, and international collaborations are critical for major research projects. For example, at CERN, physicists and engineers from nearly 100 countries collaborate on cutting-edge scientific problems (CERN, 2015). The share of publications that Canadians authored with an international collaborator increased from 41% in 2003–2008 to 46% in 2009–2014. Switzerland had the highest collaboration rate worldwide in 2009–2014, while Canada ranked seventh. Research is also becoming an increasingly international activity; between the two periods, the collaboration

21 Survey results are weighted by country of respondent to ensure that they accurately reflect the target population of researchers. For instance, Canadian researchers are slightly over-represented among survey respondents, while Chinese researchers are slightly under-represented.

rate increased for all countries except Russia, Poland, Brazil, Iran, and India. Figure 3.2 shows the share of publications of the top 20 publishing countries that have at least one international co-author.



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

Figure 3.2

Share of Scientific Publications Authored with an International Collaborator, 2003–2008 and 2009–2014

Percentages shown are based on the number of publications with at least one international collaborator as a percentage of the total number of publications (whole counts).

As noted in the 2012 S&T report, researchers in countries with larger populations tend to collaborate less internationally than those in smaller countries because the former have more opportunities to collaborate with domestic colleagues (CCA, 2012a). The Collaboration Index (CI) overcomes this bias by taking into account the size of a country's research output. When the CI score is above 1.0, a country produces more collaborations than expected based on the number of publications it produces, while a score below 1.0 indicates the reverse.

Canada had a CI score of 1.26 for the 2009–2014 period, which means that Canadian researchers collaborated 26% more than might be expected based on the total number of Canadian publications for the period. This is a slight increase from 1.21, the score noted in the 2012 S&T report for the 2005–2010 period (CCA, 2012a). On this measure, Canada ranks 7th out of the top 20 countries by number of scientific publications produced. Switzerland, the United Kingdom, and Sweden are the top three countries (Table 3.2).

3.2 CANADA'S RESEARCH PERFORMERS

In Canada, most research publications originate from a limited number of institutions (i.e., research performers). Academia accounts for almost 78% of publications (mostly universities, and excluding affiliated research hospitals) and hospitals for almost 15% (Figure 3.3). Between 2009 and 2014, the five largest universities by number of publications (University of Toronto, University of British Columbia, McGill University, University of Alberta, and Université de Montréal and their affiliated institutions and hospitals) accounted for about 37% of all Canadian publications.[22] The U15 Group of Canadian Research Universities[23] accounted for 67% of publications. Data also suggest that institutions with high specialization have a significant impact on Canadian research. For example, the Université du Québec en Abitibi-Témiscamingue (UQAT), which has a relatively small publication output, ranks fifth overall in impact. This disproportionately high impact is probably due to its specialization in Agriculture, Fisheries and Forestry (SI = 16), as most of its publications are in this field.

The combined publication share for governments and the private sector is less than 10%. The share of these performers varies greatly by field of research. For example, hospitals[24] are the second largest contributor in Clinical Medicine (almost 40% of total research publications), and Public Health and Health Services and Biomedical Research (both over 15%). Governments produce about one-third of all research publications in Agriculture, Fisheries and Forestry and are heavily involved in Astronomy and Astrophysics through NRC Herzberg Astronomy and Astrophysics Research Centre's activities. The private sector has a lower share of publication output in most fields, but accounts for over 2% in Enabling and Strategic Technologies, Engineering, and Chemistry. Finally, not-for-profit research organizations produce over 5% of all publications in Physics and Astronomy (Tables A.6, A.7, A.8 in the appendix).

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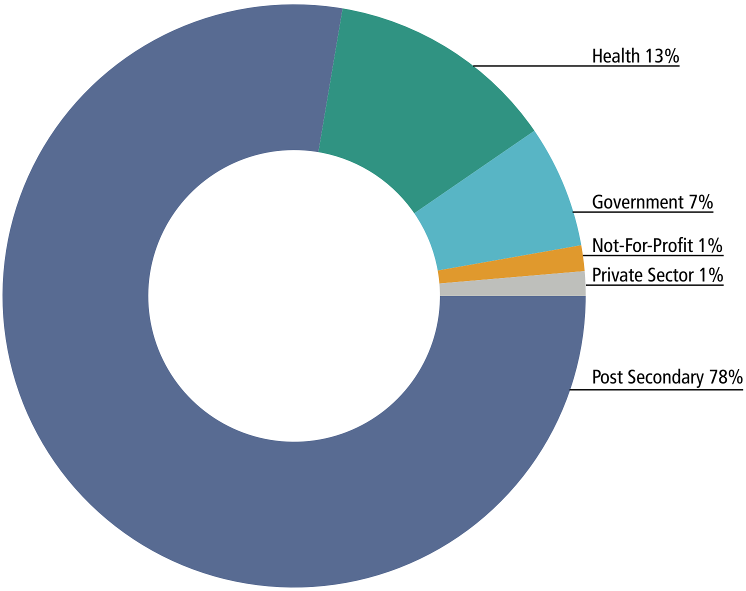
22 In 2015, these institutions accounted for 45% of sponsored research income among the top 50 Canadian research universities. According to Re$earch Infosource, sponsored research income "includes all funds to support research received in the form of a grant, contribution or contract from all sources external to the institution" (Re$earch Infosource Inc., 2016).

23 The U15 Group of Canadian Research Universities is a lobby organization for Canada's 15 largest research-intensive universities: University of Alberta, University of British Columbia, University of Calgary, Dalhousie University, Université Laval, University of Manitoba, McGill University, McMaster University, Université de Montréal, University of Ottawa, Queen's University, University of Saskatchewan, University of Toronto, University of Waterloo, and Western University.

24 Note that most hospital researchers are also faculty members paid by their universities to varying degrees because they are teaching and training highly qualified personnel; it is therefore challenging to distinguish contributions.



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

Figure 3.3

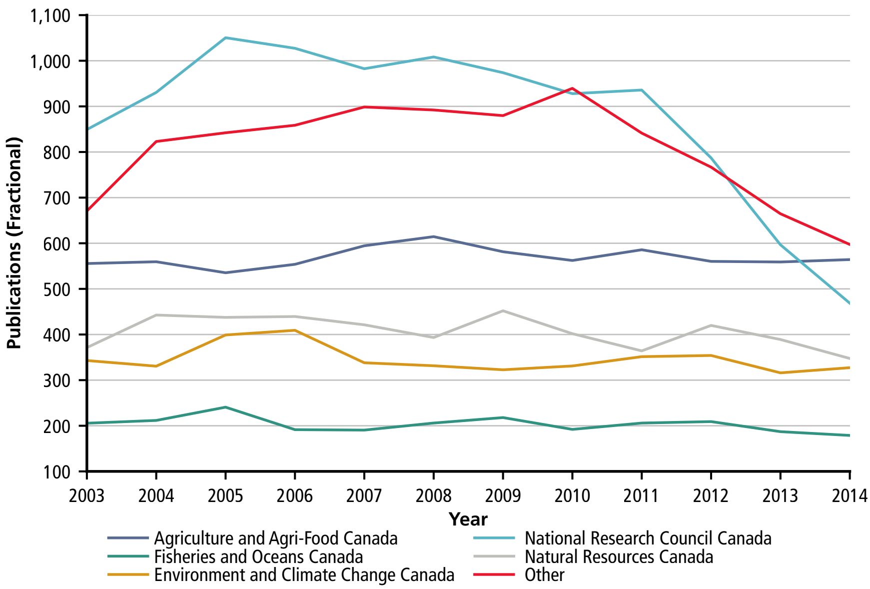
Share of Publication Output by Research Performer in Canada, 2003–2014

The figure shows the proportion of publications (in fractional counts) by research performers such as academia, health (e.g., hospitals), government departments, and other organizations.

3.2.1 Decline in Federal Government Research Output

The federal government plays a significant role in research in Canada, particularly in Agriculture, Fisheries and Forestry; Biology; and Enabling and Strategic Technologies. In 2014, the major performers of federal research were Agriculture and Agri-Food Canada (23% of total federal production), NRC (19%), Natural Resources Canada (14%), Environment and Climate Change Canada (14%), and Fisheries and Oceans Canada (7%). However, between 2009 and 2014, the number of research publications produced by the federal government significantly dropped from 3,428 to 2,484 (fractional counts) (Figure 3.4).

Among the 10 major fields of federal science, Information and Communication Technologies, Physics and Astronomy, and Chemistry experienced the greatest fall in publications between 2009 and 2014, while NRC had the largest decline among federal institutions. NRC's production dropped from about 1,050 publications (about 1,800 in full count) in 2005 to about 500 publications (or about 1,200 in full count) in 2014. However, the impact of NRC's scientific publishing is high; publications are cited 45% more than the world average and HCP1% is 1.62 for the 2009–2014 period. Overall, the organization's ARC



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

Figure 3.4

Publication Output by Federal Government Institutions in Canada, 2003–2014

The figure shows the publication output (fractional) between 2003 and 2014 of the top five federal publication institutions and "Other" (National Defence Canada, Health Canada, Atomic Energy of Canada Ltd., Communications Research Centre Canada, Public Health Agency of Canada, Bank of Canada, Bedford Institute of Oceanography, Canadian Grain Commission, Canadian Museum of Nature, Canadian Space Agency, Canadian Food Inspection Agency, Canadian Institutes of Health Research, Parks Canada, and Statistics Canada).

score rose from 1.35 to 1.45 between the 2008 and 2013, despite its recent and substantial focus on revenue-generating work for clients. This focus translated into a drop in staff time spent on exploratory research and a related decline in the overall number of NRC publications. Student hires at the NRC fell by over 80% between 2008 and 2012, and the total number of researchers employed decreased steadily from 2009 to 2015; the number of researchers remains at about 13% lower than March 2009 levels (NRC, personal communication, 2017).

Expenditure restraint, combined with an emphasis on revenue-generating work for clients to maintain capacity, contributed to shifting staff away from novel, exploratory work, which is better suited to publication, towards fee-for-service and commercial work (NRC, personal communication, 2017). Note that researchers at the NRC are ineligible to apply for grants with the Tri-Agency unless they also have adjunct status at a Canadian university or college, funding which is limited to support students. Federal policy interest in and emphasis on science and exploratory research have increased since the change of government in fall 2015. Present activity at the NRC indicates an intention to restore collaborations with universities, polytechnics, and colleges to advance knowledge and increase investments in the kinds of exploratory science that will support future growth industries.

3.3 CANADA'S INTERNATIONAL STANDING BY FIELD OF STUDY

The ranking of fields of study in Canada by number of publications is similar to that in the 2012 S&T report. The 2009–2014 rankings of the six largest research fields by absolute count of publications (Clinical Medicine, Information and Communication Technologies, Engineering, Biomedical Research, Physics and Astronomy, and Enabling and Strategic Technologies[25]) are unchanged from the 2005–2010 period — the latest used in the 2012 S&T report. Canada's overall share of total global publications decreased in most fields of research, with a few exceptions. For example, Canada's share of publications increased in Public Health and Health Services (from 6.6% between 2003 and 2008 to 7.1% between 2009 and 2014) and in Visual and Performing Arts (from 3.4 to 5.5%) (Table 3.5).

Publication output in most fields of research in Canada grew more slowly than the world average between 2003 and 2014 (Figure 3.5), except for Visual and Performing Arts (note the small sample size) and Public Health and Health Services. This is a significant change from the 2012 S&T report, which noted that half of the fields grew more quickly than the world average between 1999 and 2010 (see CCA, 2016 for more details). The Panel noted the declining trajectory in the growth of fields of research in Enabling and Strategic Technologies, Chemistry, and Physics and Astronomy.

25 This field encompasses subfields related to new or emerging technologies such as Energy, Biotechnology, Bioinformatics, Nanoscience and Nanotechnology, and Optoelectronics and Photonics.

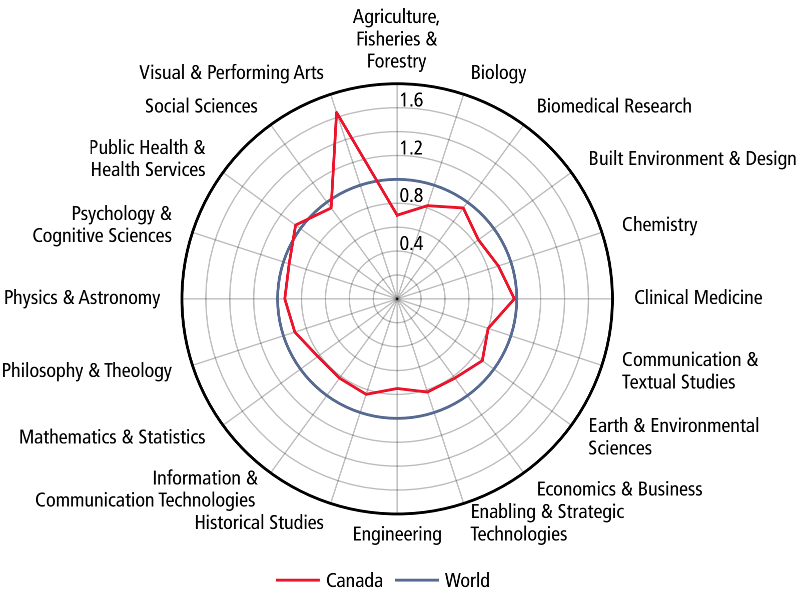
Table 3.5

Total Publication Output, Share of World Publications, and Specialization Index by Field of Research in Canada, 2003–2008 and 2009–2014

Field	Number of Publications 2009–2014		Canada's Share of World Publications		SI	
	Canada	World	2009–2014 (%)	2003–2008 (%)	2009–2014	2003–2008
Psychology & Cognitive Sciences	15,322	203,231	7.5	7.7	2.05	1.88
Public Health & Health Services	20,872	292,529	7.1	6.6	2.02	1.69
Philosophy & Theology	2,942	51,535	5.7	6.2	1.86	1.81
Earth & Environmental Sciences	19,276	349,790	5.5	5.8	1.22	1.22
Visual & Performing Arts	664	12,138	5.5	3.4	1.84	0.98
Biomedical Research	35,337	730,600	4.8	4.9	1.19	1.11
Biology	20,364	431,532	4.7	5.4	1.14	1.21
Social Sciences	17,351	367,697	4.7	4.9	1.46	1.35
Built Environment & Design	3,975	85,646	4.6	5.4	1.36	1.41
Economics & Business	12,812	284,327	4.5	5.2	1.16	1.24
Communication & Textual Studies	3,751	83,407	4.5	5.6	1.51	1.66
Agriculture, Fisheries & Forestry	16,079	361,922	4.4	5.9	1.19	1.49
Information & Communication Technologies	38,236	897,429	4.3	4.9	1.14	1.22
General Science & Technology	9,722	230,907	4.2	2.9	0.87	0.48
Clinical Medicine	106,899	2,584,581	4.1	3.9	1.05	0.94
Historical Studies	2,952	73,052	4.0	4.8	1.25	1.31
General Arts, Humanities & Social Sciences	482	13,026	3.7	3.6	1.17	0.98
Mathematics & Statistics	10,249	286,853	3.6	4.2	0.85	0.91
Engineering	37,902	1,156,209	3.3	4.2	0.90	1.06
Physics & Astronomy	33,783	1,102,228	3.1	3.0	0.65	0.60
Enabling & Strategic Technologies	32,006	1,227,152	2.6	3.1	0.71	0.76
Chemistry	18,873	796,279	2.4	2.6	0.64	0.63

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

Fields are ranked by Canada’s share of world publications between 2009 and 2014.



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

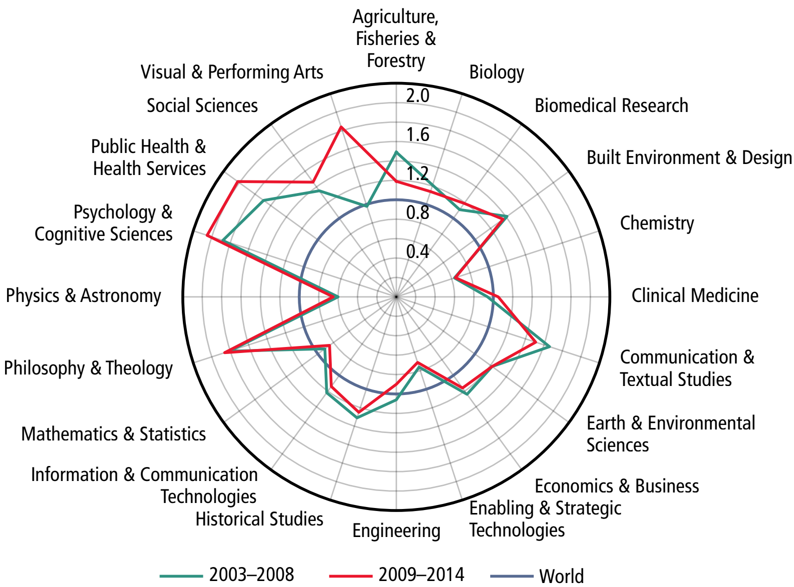
Figure 3.5

Growth Index by Field of Research in Canada and the World, 2003–2014

The figure shows Canada's Growth Index (GI) scores by field of research relative to the world GI score. The GI score is based on a comparison of growth between the 2008–2014 and 2003–2008 periods.

Compared with the world average, Canada has a relatively high concentration of research in Psychology and Cognitive Sciences, Public Health and Health Services, Philosophy and Theology, Earth and Environmental Sciences, and Visual and Performing Arts. It also has a relatively low concentration in Chemistry, Physics and Astronomy, and Enabling and Strategic Technologies (Figure 3.6). Overall, Canada's Specialization (SI) scores did not change dramatically between the 2003–2008 and 2009–2014 periods except for increases in Visual and Performing Arts[26] and Public Health and Health Services (Figure 3.6). Overall, Canada, compared to the world, specializes in the subjects generally referred to as the humanities and social sciences (plus health and the environment), and does not specialize in those areas traditionally referred to as the physical sciences and engineering.

26 Both Canada and the world have experienced strong publication growth in this field in recent years, though from a relatively small initial base. World publication output in Visual and Performing Arts roughly doubled between 2003 and 2014, rising to just over 2,000 publications. Canada's output more than quadrupled, rising from 33 publications in 2003 to 136 publications in 2014. In both cases, however, publications in this field remain a very small fraction of total publications indexed in Scopus.



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

Figure 3.6

Specialization Index by Field of Research in Canada, 2009–2014 and 2003–2008

The figure shows Canada's Specialization Index (SI) scores by field of research relative to the world.

3.3.1 Impact by Field of Study

All research fields in Canada had ARC scores above 1.0 for the 2009–2014 period (Table 3.6), indicating citation levels above the world average. A more competitive standard, however, is the average ARC for G7 countries. Six fields in Canada have both high SI and ARC (above the average ARC for G7 countries) scores: Clinical Medicine; Biology; Information and Communication Technologies; Agriculture, Fisheries and Forestry; Earth and Environmental Sciences; and Economics and Business. Some fields in Canada exhibit ARC scores below the G7 standard. The largest field is Biomedical Research. Public Health and Health Services and Psychology and Cognitive Sciences are found here as well, although in the latter case, Canada still ranks among the top five countries by ARC for the 2009–2014 period.[27] (See Figure A.2 in the appendix and CCA, 2016).

27 This tends to occur when research output is highly concentrated in several countries (e.g., United States), which allows countries to rank highly despite comparatively low ARC scores (in some cases below 1.0). See the 2012 S&T report for further discussion (CCA, 2012a).

Table 3.6
Key Indicators of Research Impact for Canada by Field, 2003–2008 and 2009–2014

Field	2009–2014				2003–2008			
	Rank by ARC	ARC	MRC	HCP1%	Rank by ARC	ARC	MRC	HCP1%
General Arts, Humanities & Social Sciences	2	1.58	2.00	2.25	9	1.11	1.67	0.93
Psychology & Cognitive Sciences	4	1.16	1.22	1.34	3	1.12	1.22	0.92
Clinical Medicine	5	1.73	1.75	2.48	2	1.62	1.75	2.08
Physics & Astronomy	5	1.54	1.50	2.09	4	1.38	1.50	1.56
Historical Studies	5	1.28	2.00	1.81	4	1.21	1.50	1.27
Visual & Performing Arts	5	1.24	–	1.64	2	1.66	2.00	2.90
Information & Communication Technologies	6	1.42	1.00	1.61	5	1.36	1.67	1.40
Economics & Business	6	1.38	1.50	1.57	6	1.17	1.33	1.25
Chemistry	6	1.28	1.50	1.35	7	1.25	1.53	1.26
Philosophy & Theology	6	1.23	2.00	1.32	10	0.93	1.00	0.65
General Science & Technology	7	1.77	1.83	2.48	6	2.22	7.80	3.11
Agriculture, Fisheries & Forestry	7	1.44	1.67	1.88	8	1.25	1.38	1.68
Biology	7	1.43	1.60	2.31	8	1.32	1.45	1.70
Social Sciences	7	1.17	1.00	1.35	10	1.09	1.33	1.08
Engineering	8	1.38	1.60	1.65	8	1.37	2.00	1.47
Earth & Environmental Sciences	8	1.33	1.50	1.64	7	1.31	1.56	1.56
Public Health & Health Services	8	1.24	1.29	1.79	6	1.28	1.36	1.56
Enabling & Strategic Technologies	9	1.34	1.40	1.47	8	1.31	1.50	1.63
Biomedical Research	9	1.25	1.25	1.56	9	1.17	1.22	1.20
Mathematics & Statistics	9	1.14	1.00	1.07	8	1.13	1.29	1.08
Communication & Textual Studies	9	1.09	1.00	1.30	8	1.02	1.00	0.99
Built Environment & Design	14	1.01	1.00	1.05	10	1.16	1.22	1.28

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

Rankings are based on ARC scores for the 2009–2014 and 2003–2008 periods and the top 20 countries by total number of publications produced in that field. See Tables A.4 and A.5 in the appendix for indicators on subfields.

Fields with the highest ARC scores (above 1.50) include Clinical Medicine and Physics and Astronomy, both of which were identified as Canadian strengths in the 2012 S&T report.[28] ARC scores for virtually all fields of research in Canada increased between the 2003–2008 and 2009–2014 periods. The only fields in which ARC scores decreased were Visual and Performing Arts, Built Environment and Design, and Public Health and Health Services, but the decrease in the latter was small. MRC scores reveal a different pattern in several cases (see CCA, 2016).

In both the 2005–2010[29] and 2009–2014 periods, Canada ranked among the top five countries by ARC score in five fields (in addition to General Science and Technology and General Arts, Humanities and Social Sciences[30]): Psychology and Cognitive Sciences, Clinical Medicine, Physics and Astronomy, Historical Studies, and Visual and Performing Arts. (See Figure A.1 in the appendix for the distribution of Canada's ARC score relative to the top 20 countries.) Canada was also over-represented in the top-cited 1% of publications for all fields in 2009–2014. Fields with HCP1% scores over 2 include Clinical Medicine, Biology, and Physics and Astronomy, as well as General Science and Technology and General Arts, Humanities and Social Sciences.

Canada's rank by ARC improved between the 2003–2008 and 2009–2014 periods in the following fields: Philosophy and Theology; Social Sciences; Agriculture, Fisheries and Forestry; Biology; and Chemistry. Its decline in 13 of 22 fields suggests a minor erosion in Canada's standing relative to other countries in most fields.[31] Canada's rank in both Clinical Medicine and Public Health and Health Services declined by more than one place. In contrast, Canada's rank in Chemistry rose from 10th to 6th place.

ARC ranks are not that meaningful in some fields for which countries have similar ARC scores (e.g., Mathematics and Statistics) (Figure A.1 in the appendix).

28 Comparison with the 2012 S&T report analysis should be interpreted with caution. See Section 3.6.1 for a discussion of the limitations of bibliometric data.

29 Period captured in the 2012 S&T report.

30 General Science and Technology and General Arts, Humanities and Social Sciences reflect publications in multidisciplinary journals, such as *Science* and *Nature*, which cannot be assigned a field based on the journal. Rankings here are out of the top 20 countries by total publications in that field of study. The inclusion of countries with fewer publications would result in changes in relative rankings. In the case of ties, countries with the same score are each given the same rank.

31 Note that many of the decreases were by only one place and that countries often switch back and forth in rankings over time due to minor fluctuations.

3.3.2 Reputation and Leadership by Field of Study

Table 3.7 shows the share of top-cited researchers who identified Canada as one of the top five countries in the world in their field of research. The results are highly consistent with the 2012 survey, showing only minor changes for most fields. Canada continues to rank among the top five countries in three-quarters of the fields. Fields with smaller numbers of respondents (e.g., Visual and Performing Arts, Communication and Textual Studies) exhibit greater volatility; thus, results from these fields should be interpreted with caution.

The survey also asked top-cited researchers about their familiarity with Canadian research institutions and Canadian researchers (Table B.1 in the appendix). Overall, top-cited researchers may be growing more acquainted with Canadian research. The share of researchers who have worked or studied in Canada, or collaborated with Canadian researchers, has increased since 2012.

3.4 CANADA'S RESEARCH STRENGTHS

The 2012 S&T report relied primarily on two measures for identifying Canada's research strengths: a field's international rank by ARC score (2005–2009) and its international rank based on the survey of top-cited researchers worldwide. These indicators, combined with information about the number and growth of research publications, pointed to six fields in which Canada excelled: Clinical Medicine, Historical Studies, Information and Communication Technologies (ICT), Physics and Astronomy, Psychology and Cognitive Sciences, and Visual and Performing Arts. Canada ranked among the top five countries in the world by ARC score for five of these fields (except ICT), and by survey rank for five fields (except Physics and Astronomy). Three of the fields (Clinical Medicine, ICT, and Physics and Astronomy) were among the largest fields in Canada by number of publications, though Canada's share of research in ICT was declining.

For comparison, this Panel repeated this analysis using updated data for the 2009–2014 period (Figure A.3 in the appendix). In the updated analysis, most fields maintained approximately the same standing relative to other advanced countries. The overall pattern of research strengths based on the latest data is little changed from the 2012 S&T report. The four fields (Clinical Medicine, Psychology and Cognitive Sciences, Historical Studies, and Visual and Performing Arts) that ranked in the top five countries by ARC and the survey in the 2012 S&T report continued to rank in the top five countries in 2017. Physics and Astronomy also continues to perform well on these measures, though its ARC rank has declined from third to fifth. The rankings for ICT are unchanged, ranking fourth according to the survey and sixth by ARC.

Table 3.7

Survey Results by Field of Study, 2012 and 2016

Field	2016 Number of Responses	2016 (%)*	2016 Rank**	2012 (%)*	2012 Rank
Visual & Performing Arts	11	92	3	55	4
Philosophy & Theology	38	72	3	79	3
Public Health & Health Services	203	58	3	58	3
Economics & Business	191	56	3	63	3
Social Sciences	249	54	3	54	3
Agriculture, Fisheries & Forestry	224	49	3	57	2
Built Environment & Design	40	36	3	29	5
Psychology & Cognitive Sciences	256	61	4	69	3
Clinical Medicine	364	42	4	43	4
Information & Communication Technologies	387	41	4	42	4
Biology	284	39	4	37	5
Earth & Environmental Sciences	413	38	4	41	4
Biomedical Research	614	35	4	37	5
Communication & Textual Studies	53	42	5	58	4
Historical Studies	66	32	5	35	5
Mathematics & Statistics	220	28	6	27	5
Physics & Astronomy	447	24	7	19	7
Engineering	623	23	7	27	7
Enabling & Strategic Technologies	442	17	8	17	8
Chemistry	422	16	8	20	7

*The percentage represents the share of top-cited researchers who identified Canada as one of the top five countries in the world in their field of research.

** Rank of Canada among all countries in the world as identified as a top five country in the field of research of the respondents. Fields are ordered by 2016 rank and then by 2016 percentage.

Based on this analysis, Canada continues to excel in the fields identified as research strengths in 2012, though its standing has declined in Clinical Medicine and Physics and Astronomy. The consistency of these scores over time is not surprising. They reflect national averages based on large numbers of publications, and are indicative of institutional research strengths that take considerable time to develop. However, differences in national ARC scores are often small, and small changes in scores can result in significant changes in rank (Figure A.1 in the appendix). Not all of these rank changes may be a meaningful indication of a change in research impact. Field-level analysis also often obscures divergent performance and trends among subfields.

3.4.1 Analyzing Research Strength Based on Magnitude, Impact, and Growth

To avoid relying exclusively on ARC and survey ranks, this Panel developed an additional methodology to identify areas of comparative research strength in Canada. In this methodology, research strength is modelled as a function of three underlying dimensions:

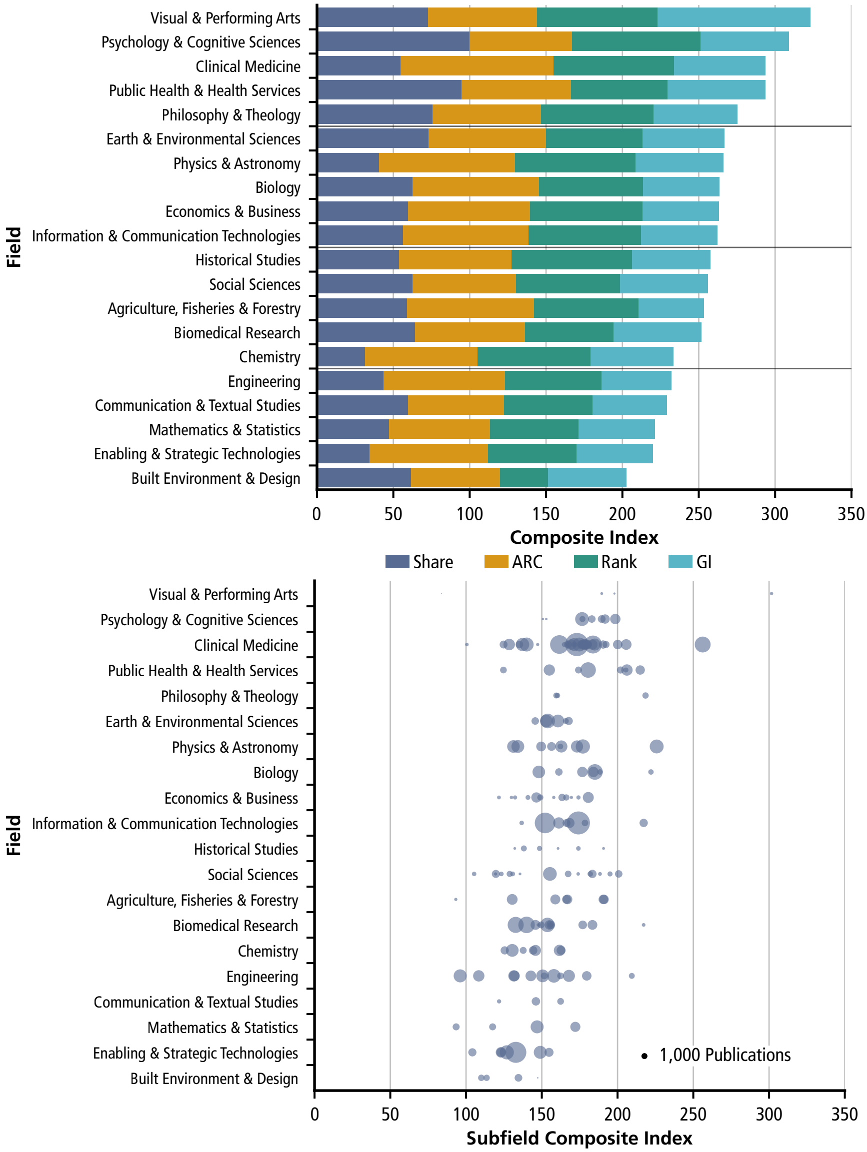
- *Magnitude:* the scale of Canada's research output relative to other countries;
- *Impact:* the influence of research on later publications as reflected by citations; and
- *Growth:* the change in research output over time relative to the world and other countries.

A composite indicator was developed to compare fields' performance based on these three dimensions. Magnitude was assessed by looking at Canada's share of world research in that field or subfield. Impact was assessed by incorporating two citation-based indicators: the ARC score, to capture Canada's position relative to the world average, and the ARC rank, which captures Canada's standing relative to other leading countries. Growth was assessed using the GI score, which reflects Canada's growth in that field or subfield relative to the world average. The composite indicator can be used to analyze performance for both fields and subfields. All four indicators included are weighted equally, giving impact a greater weight in the overall composite score than magnitude or growth. Figure 3.7 shows the results of this analysis at the field and subfield level.

3.4.2 Composite Scores for Research Fields by Quartile

Based on this approach, the full set of 20 research fields[32] can be divided into three main groups. The top quartile (i.e., top five fields) represents the strongest fields. The two middle quartiles can be grouped together, because

32 General Science and Technology and General Arts, Humanities and Social Sciences are excluded as they capture research from many fields.



Data Source: Panel calculations based on data provided by Science-Metrix using Scopus database (Elsevier)

Figure 3.7

Composite Score by Research Field and Subfield in Canada, 2009–2014

Composite scores are based on four indicators: ARC scores, ARC ranks, GI scores, and Canada's share of world publications in that field or subfield. Field scores (ARC, ARC rank, GI and share) were normalised relative to the other fields and subfields scores normalized relative to the other subfields. See Table 3.1 for definitions of these indicators. All four indicators are weighted equally. The top panel shows composite scores for fields, along with their four subcomponents. The bottom panel shows the dispersion of composite scores for subfields within each field, with the size of bubbles corresponding to the number of publications. See Table A.4 in the appendix for the composite scores of all fields and subfields.

their composite scores are closely clustered around the median. The bottom quartile then captures the fields in which Canada is less competitive with other countries based on these metrics.

The five fields in the top quartile are: Visual and Performing Arts, Psychology and Cognitive Sciences, Clinical Medicine, Public Health and Health Services, and Philosophy and Theology. These five fields excel across all the underlying indicators, though variation in the subcomponents reveals differences in the sources of their strength. Psychology and Cognitive Sciences and Public Health and Health Services in Canada, for example, both account for over 7% of world research and therefore score very high on the indicator of magnitude. Growth of research output in the Visual and Performing Arts is also notably higher than in most other fields (64% above the world growth rate in that field), which substantially contributes to Canada's high level of performance in that area. All of these fields show elevated levels of impact. Canada ranks among the top five countries by ARC score in three of these fields, and Clinical Medicine has an ARC score more than 50% above the world average (i.e., greater than 1.5). Additional facts about the fields in the top quartile are highlighted in Box 3.1.

Box 3.1
Quick Facts about Research Fields in the Top Quartile

- **Visual and Performing Arts:** This field produced only 664 publications for the 2009–2014 period and contains only four subfields. Bibliometric scores are therefore based on a relatively small number of publications and are more variable over time as a result. Since the last time period, Canada's share of publications in this field has increased by 2.1 percentage points, but its ARC rank has decreased by three places, dropping to fifth place. This field contains both the highest ranked (Drama and Theatre) and lowest ranked subfields (Folklore) by composite score.
- **Psychology and Cognitive Sciences:** This analysis confirms Canada's strength in Psychology and Cognitive Sciences despite a slight erosion in leadership. Canada accounts for 7.5% of the world's publications in this field, a decrease of 0.2 percentage points from the previous period. Although its ARC slightly increased, this field declined one rank in ARC and in the international survey, and now ranks fourth for both of these measures. Two subfields rank among the top 20 subfields: Social Psychology, and Developmental and Child Psychology.

continued on next page

- **Clinical Medicine:** Clinical Medicine is the largest field by output with 106,899 publications in 2009–2014. Despite a drop in ARC rank from second to fifth, Canada increased its share of world publications by 0.2 percentage points and its share of highly cited publications (HCP1%) from 2.1 to 2.5. Canada's leadership in Clinical Medicine is driven by four subfields ranked among the top 20 subfields: General and Internal Medicine, Respiratory System, Anesthesiology, and Pathology (Figure 3.8). Canada is particularly strong in General and Internal Medicine, which ranks second out of 174 subfields with a growth of 21% in output and a significant increase in impact (both ARC and MRC). As for most fields, the performance of Clinical Medicine subfields is variable. For example, Canada's relative performance in Pharmacology and Pharmacy, Ophthalmology and Optometry, and Legal and Forensic Medicine is particularly low.
- **Public Health and Health Services:** Public Health and Health Services accounts for 20,872 publications and Canada's share of world publications increased by 0.5 percentage points to 7.1%. The 2012 S&T report did not identify this subfield, most likely because of its poor ARC rank (eighth). Public Health and Health Services was the only field (other than Visual and Performing Arts) that grew faster than the world average. Four subfields are ranked among the top 20 subfields: Health Policy and Services, Speech-Language Pathology and Audiology, Epidemiology, and Rehabilitation. Gerontology is ranked among the bottom 20.
- **Philosophy and Theology:** Canada produced 2,942 publications in this field during the 2009–2014 period, accounting for 5.7% of the world's total. The field has a moderately high ARC score of 1.23 and ranks sixth internationally by ARC; however, Canada's research establishment is held in high esteem internationally in this field, ranking third in the survey of top-cited researchers. Both the ARC score and ARC rank have improved in this field since the past CCA State of S&T assessment. In 2012, growth in research output is moderate at 90% of the world average. However, Canada's strength in this field is due primarily to strong scores in the subfield of Applied Ethics.

The second and third quartiles are closely grouped and comprise a strong middle ground of research fields. Many of these fields are competitive with those in the top quartile on selected indicators, but suffer from weakness in a particular dimension. Physics and Astronomy, for example, is in the top five fields based on indicators of growth and impact. Its composite score is decreased, however, by a lower score related to magnitude due to a comparatively low share of world research output (3% of the world's total, compared with an average of 4% across all fields). This combination of high impact and a comparatively low share of research suggests that it represents an area of opportunity for Canada. ICT is another field with relatively high scores on the measures of impact, but lower performance on measures of magnitude and growth.

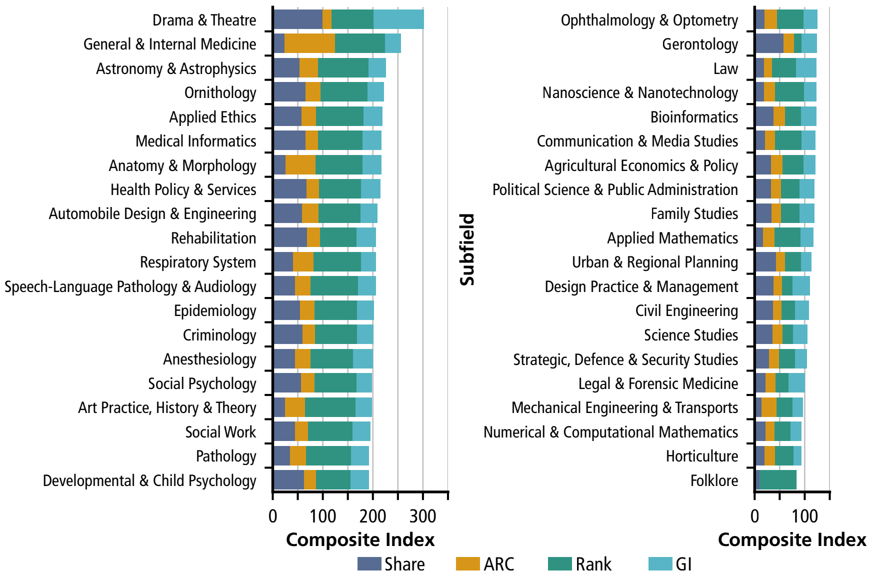
Composite scores in the bottom quartile of fields drop off more sharply. Canada's research performance in these fields is concerning and reflects weakness across all four underlying indicators. Built Environment and Design is the field with the lowest composite score by a significant measure, but Enabling and Strategic Technologies and Mathematics and Statistics also perform poorly and Chemistry and Engineering do not fare much better. These fields all suffer from lower shares of world research output, coupled with lower growth rates and less competitive ARC scores and ranks. They represent areas where Canada's research competitiveness is falling behind.

This analysis of composite scores complements the approach used for the 2012 S&T report, but offers additional insights. The absence of certain fields, identified as strengths in the previous assessment, in the top quartile here (ICT, Historical Studies, and Physics and Astronomy) reflects the inclusion of indicators of magnitude and growth. On magnitude, for example, none of these three fields score above the median on Canada's share of world publications. In ICT, Canada's share is also declining over time, dropping from 4.9% between 2003 and 2008 to 4.3% between 2009 and 2014. The ARC and survey rankings for ICT and Historical Studies remain unchanged from the 2012 S&T report, though the ARC ranking for Physics and Astronomy declined from third to fifth.

3.4.3 Composite Scores by Subfield

Field-level composite scores often mask significant variation. The individual composite scores for subfields within a field often vary widely. Visual and Performing Arts provides the clearest example of this, including both the highest ranked subfield (Drama and Theatre) and the lowest (Folklore). However, other fields also frequently show large variation in the performance on these measures within fields.

Figure 3.8 shows both the top and bottom 20 subfields by composite score. Among the top 20 subfields, Canada's strength in health-related research is clearly apparent. Several subfields in Clinical Medicine and Public Health and Health Services appear here. In psychology, Social Psychology, and Developmental and Child Psychology stand out as strengths. In the arts, Drama and Theatre and Art, Practice, History and Theory stand out, with the former ranked first of all subfields due, in particular, to growth in output well above the world average. In the natural sciences, only Astronomy and Astrophysics, and Ornithology feature among the top 20 subfields, and Criminology is the only representative from the social sciences. In subfields more related to technology, Medical Informatics and Automobile Design and Engineering stand out. The weakest performing subfields by composite score are more diverse, but include several subfields in Engineering and Enabling and Strategic Technologies.



Data Source: Panel calculations based on data provided by Science-Metrix using Scopus database (Elsevier)

Figure 3.8

Composite Scores for Top and Bottom 20 Subfields in Canada, 2009–2014

The left panel shows the composite scores for the top 20 subfields and the right shows the composite scores for the bottom 20. Composite scores are based on four indicators: ARC scores, ARC ranks, GI scores, and Canada's share of world publications in that field or subfield. See Table 3.1 for definitions of these indicators. The coloured areas within each bar correspond to the scores on the four subcomponents. All four indicators are weighted equally. See Table A.4 in the appendix for the composite scores of all fields and subfields.

The composite scores of the subfields also help illuminate important trends at the field level. In Philosophy and Theology, for example, Canada's strength mostly reflects research outputs and impacts in the subfield of Applied Ethics. This subfield ranks fifth based on the composite score. In comparison, the two other subfields in this area (Philosophy, and Religions and Theology) rank 92nd and 93rd respectively. Similarly, in Physics and Astronomy, Canada's strength is most apparent in the subfield of Astronomy and Astrophysics, which ranks 3rd; of the other eight subfields in this area, the next most highly ranked is Nuclear and Particle Physics at 49th.

3.5 ENABLING AND STRATEGIC TECHNOLOGIES

Emerging research areas are often linked to enabling technological platforms with promising future applications and potentially transformative impacts such as biotechnology, nanotechnology, clean tech, artificial intelligence (AI), and regenerative medicine. These areas attract widespread interest and funding support from governments and industry around the world, in part due to their perceived commercial and economic potential. Canada's research performance in these areas can be partially assessed through bibliometric data on specific fields and subfields and other supporting evidence.

The Panel examined emerging research areas primarily found in two bibliometric fields: Enabling and Strategic Technologies, and Information and Communication Technologies. Table 3.8 summarizes key indicators for selected subfields in these fields. The data suggest that Canada's level of research output and impact is modest in many of these research areas, and lower than that of many peer countries. Aside from Biotechnology, none of the other subfields in Enabling and Strategic Technologies has an ARC rank among the top five countries. Optoelectronics and photonics is the next highest ranked at 7th place, followed by Materials, and Nanoscience and Nanotechnology, both of which have a rank of 9th. Canada's research output in most of these areas is also low by international standards, as reflected by SI scores. Only two of these fields have SI scores above 1.0: Energy, where Canada's score of 1.05 means that output is, proportionally, very close to the world average; and Bioinformatics, with a score of 1.23. Bioinformatics is the only one of these subfields where Canada accounts for more than 4% of the world's research output. Research output and shares of world research in Biotechnology, Materials, and Nanoscience and Nanotechnology are particularly low. Moreover, none of these fields have GI scores above 1.0, meaning that output in these areas in Canada is growing less rapidly than it is globally.

In comparison, several subfields of research related to Information and Communication Technologies stand out as areas where Canada excels. Medical Informatics, in particular, appears to be an area of research where Canada has both a high level of specialization (accounting for over 8% of the world's research in this area) and a high level of impact (ranking third by ARC score among top-producing countries). Other ICT subfields where Canada ranks among the top five countries by ARC include Computer Hardware and Architecture, Information Systems, and Networking and Telecommunications. In contrast, Computation Theory and Mathematics and Distributed Computing have lower ARC rankings, and Distributed Computing and Artificial Intelligence and Image Processing stand out as the only ICT subfields here where Canada accounts for less than 4% of global output.[33] See Section 4.4.1 for more discussion of AI-related R&D in Canada.

33 The Panel noted that certain subfields in mathematics closely related to AI, such as Numerical and Computational Mathematics and Applied Mathematics, also stand out as areas of relative weakness. Both of these subfields, for example, are among the bottom 20 subfields in Canada by composite score identified in Figure 3.8.

Table 3.8

Bibliometric Indicators for Selected Subfields in Canada Related to Enabling and Strategic Technologies

Subfield	Papers (2009–2014)	Canada's Share of World (%)	SI	GI (2003–2014)	ARC	MRC	ARC 1st percentile	ARC Rank
Enabling & Strategic Technologies								
Bioinformatics	2,338	4.89	1.23	0.92	1.15	1.20	1.32	14
Biotechnology	2,253	2.40	0.63	0.84	1.44	1.60	2.32	5
Energy	12,232	3.70	1.05	0.97	1.22	1.50	1.33	11
Materials	5,573	1.34	0.36	0.67	1.77	2.33	1.75	9
Nanoscience & Nanotechnology	3,086	2.44	0.65	0.74	1.07	1.25	0.80	9
Optoelectronics & Photonics	4,659	2.87	0.77	0.83	1.51	1.00	1.91	7
Information and Communication Technologies								
Artificial Intelligence & Image Processing	11,796	3.12	0.83	0.76	1.43	1.00	1.60	6
Computation Theory & Mathematics	3,527	5.84	1.43	0.85	1.23	1.50	0.92	8
Computer Hardware & Architecture	1,179	4.83	1.33	1.11	1.26	1.00	1.26	5
Distributed Computing	570	3.66	0.87	0.68	1.12	1.00	1.51	8
Information Systems	1,751	4.23	1.04	0.86	1.29	2.00	1.13	5
Medical Informatics	1,927	8.66	2.53	1.14	1.16	1.33	1.35	3
Networking & Telecommunications	14,668	4.83	1.32	0.81	1.53	1.00	1.93	5
Software Engineering	2,818	5.53	1.50	0.90	1.35	1.50	1.56	7

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

Bibliometric indicators suggest that Canada's research contributions and impact are only modest in many subfields related to emerging or strategic technologies. However, some ICT subfields, such as Medical Informatics, represent areas of comparative strength based on these measures.

The Advisory Panel for *Canada's Fundamental Science Review* recently undertook a similar analysis (Advisory Panel for the Review of Federal Support for Fundamental Science, 2017). It assessed Canada's research performance in 15 emerging research fields based on their potential for early application, rapid growth in global publications and citations, and identification by peer nations as strategic priorities for enhanced funding. The Advisory Panel found that Canada's research output is stalling or starting to decline in many areas relative to China and other countries (Advisory Panel for the Review of Federal Support for Fundamental Science, 2017). Canada ranked among the top five countries by publication output in only one area (Personalized Medicine), and ranked 10th or lower in one-third of them. This led the Advisory Panel to conclude that "it appears that Canada has briefly claimed bragging rights in certain fields based on excellence in one or two centres, but systematically failed to build national capacity that would create an enduring advantage" (Advisory Panel for the Review of Federal Support for Fundamental Science, 2017).

The impression that emerges from these data is sobering. With the exception of selected ICT subfields, such as Medical Informatics, bibliometric evidence does not suggest that Canada excels internationally in most of these research areas. In areas such as Nanotechnology and Materials science, Canada lags behind other countries in levels of research output and impact, and other countries are outpacing Canada's publication growth in these areas — leading to declining shares of world publications. Even in research areas such as AI, where Canadian researchers and institutions played a foundational role, Canadian R&D activity is not keeping pace with that of other countries and some researchers trained in Canada have relocated to other countries (Section 4.4.1). There are isolated exceptions to these trends, but the aggregate data reviewed by this Panel suggest that Canada is not currently a world leader in research on most emerging technologies.

3.6 DATA LIMITATIONS

Bibliometrics are an imperfect measure of research performance, especially in fields where journal publications are not always the primary output. Many fields in the social sciences, humanities, and arts, as well as in the applied sciences, are not well served by quantitative metrics alone. The opinion survey data gathered for this assessment may partially offset these deficiencies, though it too has limitations. Data from some types of institutions such as colleges and polytechnics are less well-developed. Additional rigour and accuracy could potentially be introduced through more widespread use of peer review processes, such as those relied on in the large-scale research assessment exercises in the United Kingdom and Australia. However, these evaluations are also imperfect, contentious, and resource intensive. The Panel is hopeful that Canada will continue to explore alternative approaches to a national research assessment that would better capture the full range and variety of contributions that researchers make across all fields of study in the future.

3.6.1 Bibliometric Analysis

Bibliometric data are a standard source of information on research performance and, at the level of nationally aggregated research fields and subfields, many bibliometric indicators are sufficiently reliable to provide useful insights.[34] At the same time, bibliometric data and analysis are subject to well-documented limitations (CCA, 2012b).

Bibliometric indicators are more appropriate for the natural and health sciences — where peer-reviewed journal articles are the primary research output — than for the social sciences and humanities, where research is often published in non-indexed publications such as books, book chapters, and other forms of output (Archambault *et al.*, 2006). Bibliometric analysis is also biased towards English-language publications due to their more extensive coverage in the database, a fact that potentially disadvantages non-English-speaking countries or provinces such as Quebec, particularly for research in the social sciences and humanities (Archambault *et al.*, 2006). It is also less suitable for research with a regional or local focus (e.g., Canadian history and culture) because regionally specific research is less likely to be published in journals indexed in Scopus and more likely to attract a regional audience and proportionally fewer citations. Comparison with the analysis in the 2012 S&T report should be interpreted with caution: publications have had more time to accrue citations and additional journals have been added to the Scopus database.[35] Due to the need for a three-year time lag between the year a study is undertaken (2016 in this case) and the latest year for which the impact measure can be calculated, impact indicators were calculated for publications for the 2003–2013 period rather than for the 2003–2014 period.

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34 Bibliometric indicators are generally recognized to be more reliable and informative in proportion to the number of publications for which an indicator is calculated (Moed, 2005). Using them in the evaluation of the research output of individual researchers or research labs is consequently more problematic. For this study, no indicators are computed unless they are based upon 30 or more publications, and scores based on 100 or fewer publications should be treated with caution. In addition, all indicators used here are field-normalized to account for the variation in publication and citation practices across fields of research.

35 This study reports bibliometric data from two six-year periods, 2003–2008 and 2009–2014, allowing for a comparison of trends over time. Note that direct comparisons with results in the 2012 S&T report, which included data from the 1999–2004 and 2005–2010 periods, may be inappropriate given changes in the database over time.

The structure of research fields and subfields can affect the outcome of bibliometric analysis. In some cases, a taxonomy of research fields may group together very distinct bodies of research, making the interpretation of results more challenging. In the Science-Metrix taxonomy used here, for example, the field of Historical Studies includes the subfield of History but also those of Anthropology, Archaeology, and Paleontology. Similarly, the field of Philosophy and Theology aggregates different areas of research that are not related. Such challenges occur with any taxonomy, however, and can partially be mitigated by analyzing data at the subfield level. Standard taxonomies of research fields also sometimes obscure the importance of interdisciplinary and multidisciplinary research. Canada's research output related to Arctic science, for example, is dispersed across many fields in a traditional taxonomy (e.g., environmental science, geography, meteorology, oceanography, ecology, anthropology), making it harder to analyze this cross-cutting area. The subject of a publication may cover two fields of research (e.g., Medical Informatics). The same is true for other emerging fields such as cyber security, which is not a stand-alone field in the Science-Metrix taxonomy despite its growing importance to national security.

Finally, and most critically, bibliometric analysis captures only one form of research impact: effects on current and future knowledge generation as demonstrated through publications. Research in some fields may give higher priority to other types of socially beneficial impacts. For example, in applied research domains (e.g., engineering, computer science, design), publications may be less important than technological advances or measures based on outputs such as patents, industrial designs, or trademarks. Much social sciences and humanities research is also oriented towards outcomes other than publications. As one example, the activities of the Truth and Reconciliation Commission of Canada used research methods from many humanities and social sciences disciplines, as well as oral testimony and Indigenous ways of knowing, to produce its report. This research prioritized informing public policy, contributing to cultural discussion and dialogue, and improving individual and social well-being among Indigenous Peoples in Canada. Other examples could be drawn from legal scholarship and education research. In short, the numbers of publications and citations will always be partial and insufficient measures of the impact and importance of research in such cases, while providing useful and internationally comparable evidence in other areas.

3.6.2 International Survey of Top-Cited Researchers

The primary limitation of the survey data is that it reflects the perceptions and opinions of top-cited researchers, which may be skewed by cognitive or personal biases. Such biases have been widely studied and discussed (see, for example, Tourangeau, 2003 and Oskamp & Schultz, 2005). Survey results may also suffer from response bias; individuals more familiar with Canada may have been more likely to respond to the survey. The implications of such bias for survey results could be either positive or negative. Other potential biases exist in the data but can be statistically controlled. For example, survey results are weighted in this analysis to ensure that certain countries are not over- or under-represented. The number of respondents also varies considerably by research field and subfield. Results from fields with small numbers of respondents should be interpreted with caution. Fields in the humanities and arts, for example, attracted smaller numbers of respondents due to their proportionally smaller publication output. These limitations are discussed in more detail in the 2012 S&T report (CCA, 2012a).

3.7 CONCLUSION

Despite these limitations, the data assembled in this chapter are comprehensive enough to generate key insights about the overall output and impact of R&D in Canada. On balance, they suggest that Canada is maintaining its standing as a key contributor to the world's research output. Canada still punches above its weight (by population and by GDP) when it comes to academic publications and citations, and excels in many fields. Canada's rank by ARC score remains unchanged at sixth place since the 2012 S&T report, though there has been a modest erosion in Canada's international standing in some fields. Canadian researchers are also highly collaborative and becoming more so over time, with Canada ranking seventh out of the top 20 countries on an index of collaboration.

Based on the Panel's analysis of research magnitude, impact, and growth, Canada especially excels in the fields of Visual and Performing Arts, Psychology and Cognitive Sciences, Clinical Medicine, Public Health and Health Services, and Philosophy and Theology. A robust record of ongoing, high-impact research contributions in these areas is also indicative of the underlying strength of Canada's research talent and infrastructure in these fields. Behind every highly cited publication is a researcher who has invested decades in developing their expertise and skills, and whose work is often supported by access to world-leading equipment and facilities.

Two points, however, stand out as causes for concern. First, Canada has a relatively low level of specialization in core disciplines in the natural sciences and engineering, and its contributions in these fields are comparatively less esteemed by top-cited researchers around the world. Under-development in these fields may impair Canada's research flexibility in the future, preventing research institutions and researchers from being able to pivot to tomorrow's emerging research areas. Second, as noted, Canada's research output and impact in fields of emerging, enabling, and strategic technologies are below what might be expected based on its general research performance. These are subfields of research where Canada appears to be falling behind many countries. Given the potentially transformative role of research emerging from these areas of study, Canada's ability to participate in — and benefit from — future developments in these areas may be at risk.

4

Canada's Industrial R&D

- Key Trends in Canadian Industrial R&D Spending
- Industrial R&D Outputs: Patents, Trademarks, and Designs
- Canada's Industrial R&D Strengths
- Industry Profiles
- Data Limitations
- Conclusion

4 Canada's Industrial R&D

Key Findings

There has been a sustained erosion in Canada's industrial R&D capacity and competitiveness.

- Canada ranks 33rd of 40 OECD and other leading countries on an index measuring industrial R&D spending, intensity, and growth between 2006 and 2015.
- While Canada is the ninth largest employer of industrial R&D personnel, it is one of the few leading countries with negative industrial R&D employment growth between 2004 and 2013.

Compared with other G7 countries, much of Canada's R&D is carried out in less R&D-intensive industries.

- About 50% of Canada's industrial R&D spending is in high and medium-high tech sectors (including industries such as ICT, aerospace, pharmaceuticals, and automotive) compared with the G7 average of 80%. Canadian BERD intensity was also below the G7 average in these sectors in 2011.
- At around 50%, Canada's R&D investment in low and medium-low tech sectors (including oil and gas, wholesale trade, and cultural industries) is substantially more than the G7 average (17%) and at a much higher intensity in some cases.
- This spending reflects Canada's long-standing industrial structure and patterns of economic activity.
- Despite Canada's weak spending on industrial R&D, many Canadian industries, such as agriculture, wholesale and retail trade, and finance and insurance, have achieved G7-leading productivity growth through the adoption of new production methods and technologies.

Canada's industrial R&D activity is shifting in response to global and domestic trends in industrial sector, firm size, and foreign ownership.

- Nearly 60% of Canada's R&D spending is in the services sector with manufacturing R&D declining overall.
- R&D spending has become more concentrated in larger firms in recent years, though SMEs still account for a proportionately larger share of R&D in Canada than in the United States.
- At 36% of total R&D, the share of R&D under foreign control in Canada is increasing, reflecting a shift towards MNEs locating R&D operations outside their home country.

continued on next page

Canada's share of patent applications is about 1% of the world's total. Patents invented in Canada are increasingly owned outside the country.

- Canadian patents granted by the USPTO is most concentrated in Computer Technology, Civil Engineering, Digital Communication, and Telecommunications.
- Canada is now a net exporter of patents and the patent outflow is accelerating, particularly in Electrical Engineering, Telecommunications, and Digital Communication patents.

Based on a composite indicator of magnitude, intensity, and growth, the Panel classified four industries of R&D strength:

- Scientific research and development services
- Computer systems design
- Communications equipment manufacturing
- Aerospace products and parts manufacturing

Between 2014 and 2017, Canadian business R&D is projected to decline by 2.8% per year, with more than half of this decline in oil and gas extraction and software publishing.

- Only four industries invested more than $1 billion in R&D: scientific R&D services, computer systems design, aerospace products and parts manufacturing, and software publishing.
- Among the sixteen industries projected to spend more than $250 million on R&D, only six increased their spending on R&D lead by chemical manufacturing, telecommunications services, finance, pharmaceutical manufacturing, scientific R&D services, and machinery wholesale.

New or better ideas are central to innovation and wealth creation. Some ideas are born in universities, eventually making their way into journals, books, and sometimes into designs, patents, other forms of intellectual property (IP), and start-ups. Others begin their lives outside universities, originating in garages, incubators, companies, and other places where people think, tinker, and create. Regardless of birthplace, most ideas that become innovations and generate wealth do so from industry. Industrial R&D is a core component of this business innovation process (CCA, 2009).

Industrial R&D spending is correlated with multifactor productivity (MFP), labour productivity, and GDP growth (CCA, 2013a; Jones, 2016). The more industry invests in R&D, the greater that country's innovation, wages, and incomes are likely to be because innovation talent is being developed. While just one determinant of innovation, industrial R&D spending is important.

The most reliable estimates suggest that the rate of return on industrial R&D spending is strongly positive, generally between 20 and 30% (Hall *et al.*, 2010). R&D investment is likely to become more important as the global economy becomes increasingly driven by advances in AI, biotechnology, and emerging technologies.

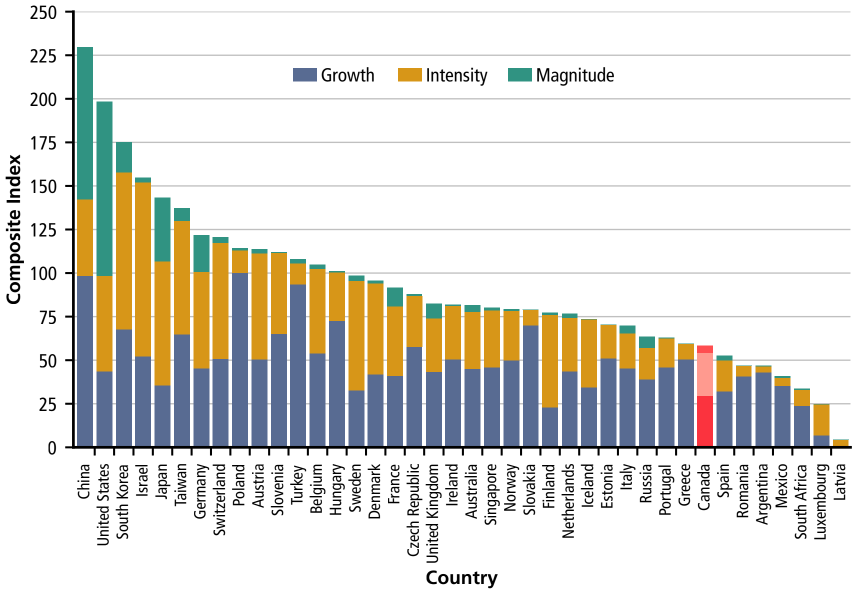
On average, industry carries out nearly 70% of the R&D undertaken in OECD countries (OECD, 2016a). In Canada, this share is notably smaller, with industry accounting for just 50% of all Canadian R&D spending. Section 4.1 examines how this spending compares with that of G7 and OECD countries and reviews three explanations for this spending gap: industrial structure, firm size, and firm ownership. Section 4.2 reviews Canadian IP, a key output of industrial R&D. Section 4.3 identifies Canada's current industrial R&D strengths. Since aggregate statistics often fail to capture key insights about how Canadian industries are evolving due to widespread data limitations, Section 4.4 provides a more detailed assessment of four Canadian industries: ICT, aerospace manufacturing, pharmaceutical manufacturing, and oil and gas extraction. Section 4.5 discusses data limitations and Section 4.6 concludes.

4.1 KEY TRENDS IN CANADIAN INDUSTRIAL R&D SPENDING

4.1.1 National Spending

Chapter 2 indicates how far behind most peer countries Canada has fallen in industrial R&D spending. Based on a composite indicator that weights industrial R&D magnitude, intensity, and growth over the 2006–2015 period, Canada ranked 33rd among 40 OECD and other leading countries (Figure 4.1). Canada now lags well behind global leaders such as China, United States, and South Korea, mostly due to low spending intensity (0.9%) and declining spending (–0.7%).[36] Although Canada is the 11th largest spender on industrial R&D, the intensity and growth of this spending are well below the OECD average. Canada's industrial R&D spending was about 55% of the OECD average in 2015. Adjusted for inflation, industrial R&D declined slightly in Canada between 2006 and 2015, while across the OECD it grew at an average rate of 2.6% per year. (Table D.1 in the appendix presents data for the 15 countries that spent the most on industrial R&D in 2015.)

36 Note that this analysis is for the period 2006–2015. The analysis of BERD growth rates in Section 2.1 is for the 2010–2015 period.



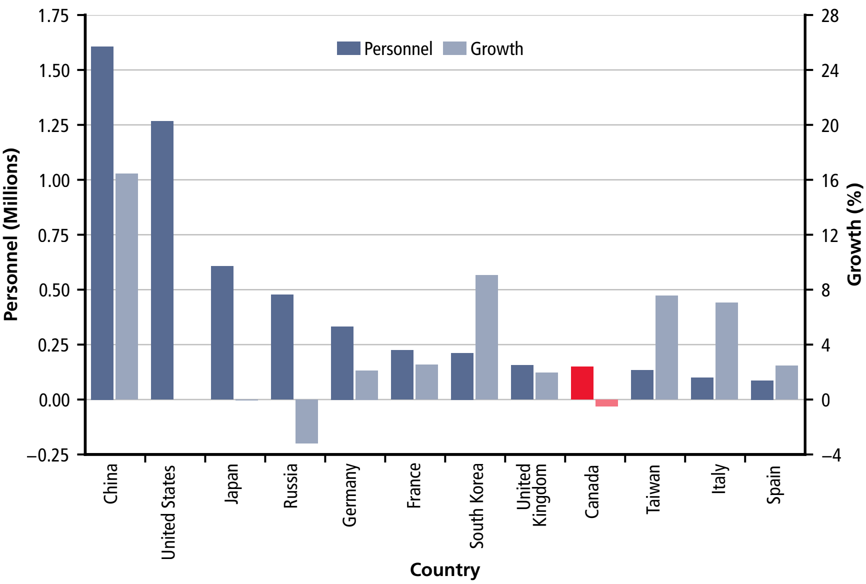
Data Source: OECD (2016a) and Panel calculations

Figure 4.1

Industrial R&D Spending, OECD and Other Selected Countries, 2006–2015

The figure ranks countries based on a composite indicator of industrial R&D spending, taking into account: magnitude (BERD in 2015, in US dollars adjusted for purchasing power parity), intensity (BERD-to-GDP ratio in 2015), and growth (BERD compound annual growth rate, 2006–2015, at constant prices adjusted for purchasing power parity). Each component is adjusted as a fraction of 100, implying a maximum score of 300. Canada ranks 33rd, with a composite score of 58.

Canadian industry employed an average of 150,000 people in R&D during the 2004–2013 period, making it the ninth largest employer of R&D personnel in the world. Yet, in 2013, fewer R&D personnel (132,000) were working in industry than in 2008 (173, 000), with the number individuals employed in this capacity having declined 20% from its peak in 2008 (Figure 2.11). As shown in Figure 4.2, Canada is one of the few leading countries with declining R&D employment in industry, a trend which likely reflects the overall decline in industrial R&D expenditures.



Data Source: OECD, 2016a

Figure 4.2

Industrial R&D Personnel, Top 12 Countries, 2004–2013

The figure ranks countries based on the average number of R&D personnel employed in industry during the 2004–2013 period. Canada employed an average of 150,000 R&D personnel per year during the period. Along with Japan and Russia, Canada experienced negative employment growth (CAGR) over the period. Data are unavailable to calculate U.S. growth during the period.

4.1.2 Sector Spending

Historically, industrial R&D activity was concentrated in the manufacturing sector (CCA, 2009, 2013b), but this is no longer true today. R&D spending in the manufacturing sector sharply declined between 2006 and 2016 from about 54 to 34% of national spending (Table 4.1). This reflects both a global shift of R&D towards the services sector and contractions in Quebec and Ontario pharmaceutical and automotive manufacturing (see Section 4.4).

In 2016, the services sector expected to spend almost twice as much the manufacturing sector ($9.8 billion versus $5.7 billion), but its R&D intensity (i.e., R&D expenditures relative to GDP) was much lower (0.8% versus 3.3%). Spending in ICT industries[37] remained stable from 2006 to 2016, representing about 32% of industrial R&D spending in Canada (StatCan, 2017g).

37 An aggregate constructed by Statistics Canada composed of 13 separate North American Industry Classification System (NAICS) codes.

Table 4.1
BERD Spending by Sector in Canada, 2006–2016

Sector	Magnitude (Millions $)	Intensity (%)	Share (%)	Share (%)	
	2016			2013	2006
Agriculture, forestry, fishing, and hunting	63	0.2	0.4	0.5	0.7
Mining, quarrying, and oil and gas extraction	789	0.6	4.7	9.9	4.4
Utilities	164	0.4	1.0	1.4	1.9
Construction	69	0.1	0.4	0.5	0.5
Manufacturing	5,706	3.3	34.3	42.0	53.7
Services-producing industries	9,825	0.8	59.1	45.7	38.7
Total	16,621	1.0	100.0	100.0	100.0
Information and communication technologies (ICT)	5,385	7.3	32.4	30.8	32.0

Data Source: StatCan, 2017f, 2017j, 2017o, 2018

The table provides R&D spending for Canada's economic sectors. Share of total industrial R&D spending is presented for 2006, 2013, and 2016. Magnitude and intensity are only presented for 2016 and are based on the new Statistics Canada survey methodology. ICT is an aggregation of ICT-related manufacturing and service industries and therefore appears below the total. In this table, intensity is calculated as the ratio of R&D expenditures to GDP.

Compared with G7 countries, Canada's portfolio of R&D investment is more concentrated in technology sectors that are intrinsically less R&D intensive (Table 4.2). The OECD groups industries into five sectors based on their R&D intensity (Galindo-Rueda & Verger, 2016). In high and medium-high tech sectors, industrial R&D is central to the business strategy, with average R&D intensities of more than 20% and 5%, respectively. For aerospace, ICT, and pharmaceutical firms, for example, effective R&D is essential for a full pipeline of airplanes, phones, and drugs. Between 2009 and 2013, about half of Canada's portfolio (47%) was invested in high and medium-high tech sectors, substantially less than the G7 average (77%). Spending growth lagged well behind the G7 average in these two sectors.

By contrast, for low and medium-low tech sectors, industrial R&D is less important to overall business strategy. In most natural resource industries and many services industries, R&D intensity is less than 1%. Firms in oil and gas, wholesale trade, and finance industries rely less on industrial R&D to produce their goods and services. During the 2009–2013 period, around half of Canada's portfolio of industrial R&D investment was in low and medium-low tech sectors, substantially more than the G7 average (17%) and at a much higher intensity in some cases (see Section 4.3). This pattern of investment reflects long-standing concentrations of economic activity and Canada's role in the integrated North American economy (CCA, 2009; Nicholson, 2016).

Table 4.2

BERD Share, Intensity, and Growth, by Technology Sector, 2009–2013

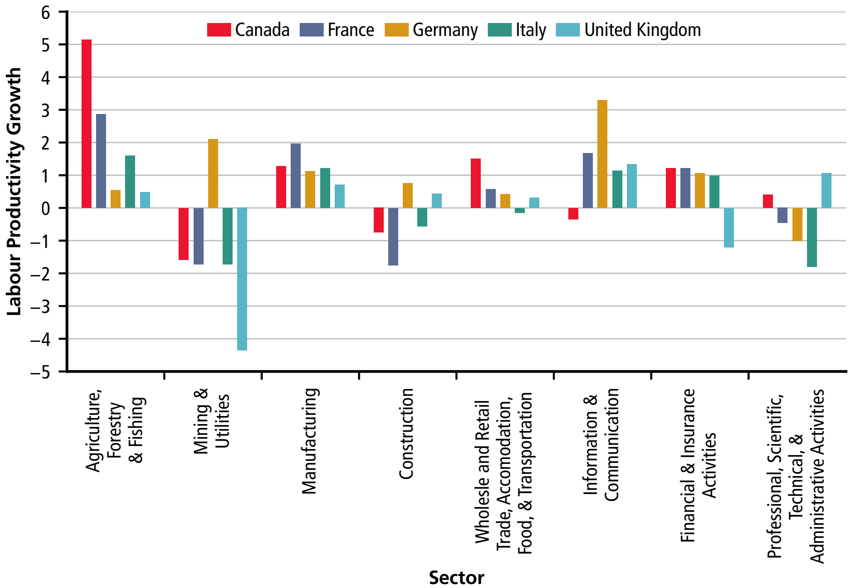
Technology Sector	Share of BERD (2009–2013) (%)		Intensity (2011) (%)		Growth (2009–2013) (%)	
	Canada	G7	Canada	G7	Canada	G7
High	31	48	25.44	28.61	–4.86	2.53
Medium-High	16	29	3.07	8.47	–3.61	7.27
Medium	3	6	1.62	2.75	–7.62	1.06
Medium-Low	34	14	2.19	1.22	–3.33	–0.56
Low	16	3	0.22	0.17	2.08	4.32

Data Source: OECD (2017a, 2017c) and Panel calculations

The table presents international (ISIC Rev. 4) industrial R&D data for the OECD's five technology sectors. It compares Canada with the G7 average in BERD share, BERD intensity, and growth. See Table D.2 in the appendix for the classification of technology sector by industry.

That industrial R&D is less central to Canadian business strategy is reflected in productivity statistics. Labour productivity depends on labour quality, capital intensity (especially ICT investment), and MFP (Baldwin & Gu, 2009; CCA, 2013c). Although industrial R&D is but one determinant of labour productivity, it is worth noting that Canada's labour productivity growth mostly mirrors the trends in industrial R&D spending. It is growing fastest in low R&D-intensive sectors such as agriculture, wholesale and retail trade, and finance and insurance (Figure 4.3).

Between 2009 and 2013, Canada's labour productivity growth was lower than the G7 average in manufacturing and ICT (where Canada was the only country with negative average growth over the period) (OECD, 2017b). These sectors include high-tech industries such as pharmaceutical manufacturing and software publishing. Canada risks falling further behind and out of step with the global economy if industrial R&D spending continues to decline. Notably, labour productivity growth was negative between 2009 and 2013 in the mining sector. Box 4.1 considers the relationship between R&D spending, MFP, and labour productivity (see Chapter 6 for further discussion on the relationship of R&D to innovation).



Data Source: OECD, 2017b, 2017d

Figure 4.3

Labour Productivity, Selected G7 Countries, 2009–2013

The figure presents labour productivity growth by sector for the 2009–2013 period. Canada is the only country with negative labour productivity growth in ICT.

Box 4.1
R&D Spending, Multifactor Productivity, and Labour Productivity

Industrial R&D spending is strongly correlated with MFP and labour productivity (Jones, 2016). While Canada's industrial R&D spending has been deteriorating, Canada's MFP and labour productivity growth ranked 9th of 18 leading countries between 2006 and 2015. Yet, both quantities grew by less than 1% per year between 2006 and 2015 (OECD, 2017d).

Canada seems to have been innovative and productive despite weak industrial R&D spending. As discussed in Chapter 6, many Canadian companies describe themselves as innovative. Between 2010 and 2012, more than 75% of firms in scientific R&D services, computer systems design, architecture and engineering, and information and cultural industries reported having introduced an innovation (OECD, 2015a; STIC,

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2015). Nonetheless, increasing industrial R&D investment would likely increase both MFP and labour productivity growth partly through the development of talented people. MFP and labour productivity growth are thus correlated with the composite indicator of industrial R&D spending.

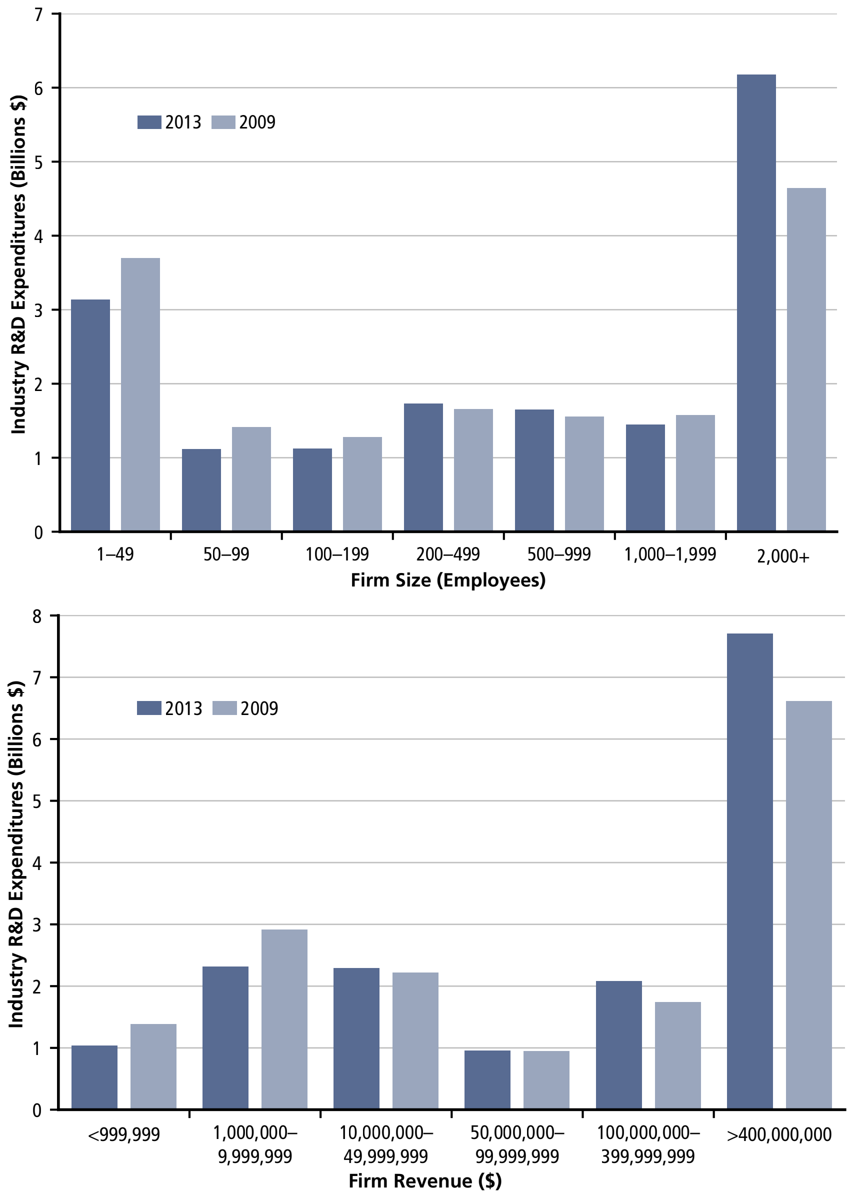
4.1.3 Firm Spending

There is some evidence that larger firms are more likely, on average, to perform R&D activities than smaller firms (Songsakul *et al.*, 2008; Cohen, 2010; CCA, 2013b). Recently, West (2017) has shown that R&D intensity and revenue grow more slowly in companies as they age, implying the opposite relationship (since older companies are, on average, larger). While the relationship between firm size and industrial R&D activity is under debate, it is clear that a greater proportion of large industrial R&D firms signals the translation of R&D into wealth creation.

R&D spending is concentrated in large firms in Canada. While only 0.3% of Canada's companies are considered large, these 2,933 companies accounted for about 52% of industrial R&D spending between 2009 and 2013 (ISED, 2016; StatCan, 2017k, 2017l). As shown in Figure 4.4, spending became more concentrated during this period. The largest firms, by both employment size (i.e., 2,000 or more employees) and revenue (i.e., $400 million or more annual revenue), invested more in industrial R&D than smaller firms (Figure 4.4).[38] Yet, despite this concentration, small and medium-sized enterprises (SMEs) perform a greater share of industrial R&D in Canada than in the United States. In 2011, firms with more than 500 employees accounted for over 81% of U.S. industrial R&D (OECD, 2017a). Given the global shift in R&D towards larger firms across all OECD countries (OECD, 2017a), it seems likely that Canadian R&D will continue to concentrate in large firms.

Firms both perform R&D in-house and contract it to other firms such as those in the scientific R&D services industry. In 2013, Canadian firms reported contracting out around $3.3 billion in R&D, a significant decline from over $4 billion in 2007 (Figure 4.5). Most of this R&D (around $2.8 billion) was contracted to business enterprises. The remainder was contracted to the higher education sector (8%) and other organizations and individuals (8%).

38 In Canada and the United States, this difference is not simply a function of size; in both countries, firms with over 500 employees account for 0.3% of all firms.



Data Source: StatCan, 2017k, 2017l

Figure 4.4

Industrial R&D Expenditures by Firm Size and Firm Revenue in Canada, 2009 and 2013

Between 2009 and 2013, there was a shift towards R&D performed at larger firms in Canada. The amount of R&D conducted at small firms (1-49 employees) decreased, but increased at large firms (more than 1,999 employees). Similarly, R&D spending became more concentrated in firms with revenues of over $400 million per year.

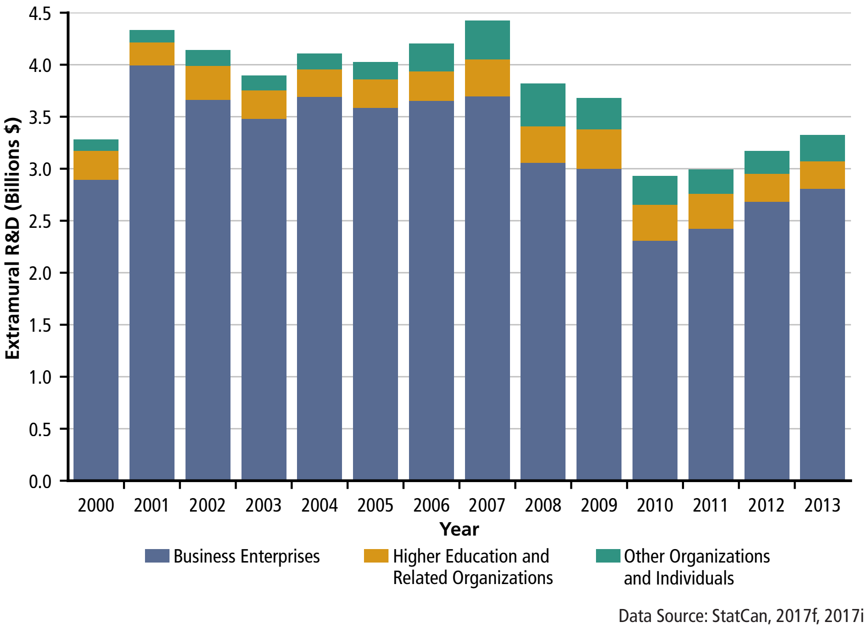


Figure 4.5

Business Extramural R&D Payments by Sector of Recipient in Canada, 2000–2013

Businesses in Canada contracted out approximately $3.3 billion in R&D in 2013, of which the large majority was to other businesses. Since 2000, the amount of R&D contracted by businesses to the higher education sector has ranged between $200 and $400 million, and was lower in 2013 than in 2000.

4.1.4 Foreign Spending

The amount of in-house industrial R&D in Canada under foreign control has fluctuated over the years, but gradually increased from 30% in 2000 to around 36% in 2013 (Figure 4.6). In 2013, $6.1 billion of in-house R&D in Canadian firms was under foreign control. The United States accounted for more than half of that total ($3.7 billion). The extent of foreign involvement does not differ significantly between the manufacturing and services sectors, which together account for the majority of industrial R&D. The small amounts of R&D in the utilities and construction sectors, however, are almost entirely Canadian-controlled.

This trend of increasing foreign control has been explained by a recent tendency of large multinational enterprises (MNEs) to move their R&D operations away from their home base to other host countries. This is the case in Canada with Google, General Motors, and Microsoft recently expanding operations to Montréal, Markham, and Waterloo, respectively. Quantitative and qualitative data seem to suggest that Canada is benefitting from this shift as MNEs are “trying to leverage Canadian research capabilities in critical emerging technologies" (Wolfe, 2017). For example, in 2016, Chinese telecom company Huawei announced its decision to invest $316 million in an R&D project focused on 5G technology in Ontario (CGE, 2016). Between 2014 and 2016, Huawei also moved from 44th to 25th place on the list of *Canada's Top 100 Corporate R&D Spenders* (Re$earch Infosource Inc., 2018).

This growth in foreign spending is a signal that many MNEs consider Canada an attractive location to perform R&D. Locating industrial R&D activity in Canada provides foreign companies with access to Canada's world-class research talent, facilities, and programs. For example, an MNE with an R&D centre in Canada would be eligible to apply to NSERC partnership programs such as Collaborative Research and Development Grants or Industrial Research Chairs Grants, allowing them to tap into Canadian academic expertise and federal funds.

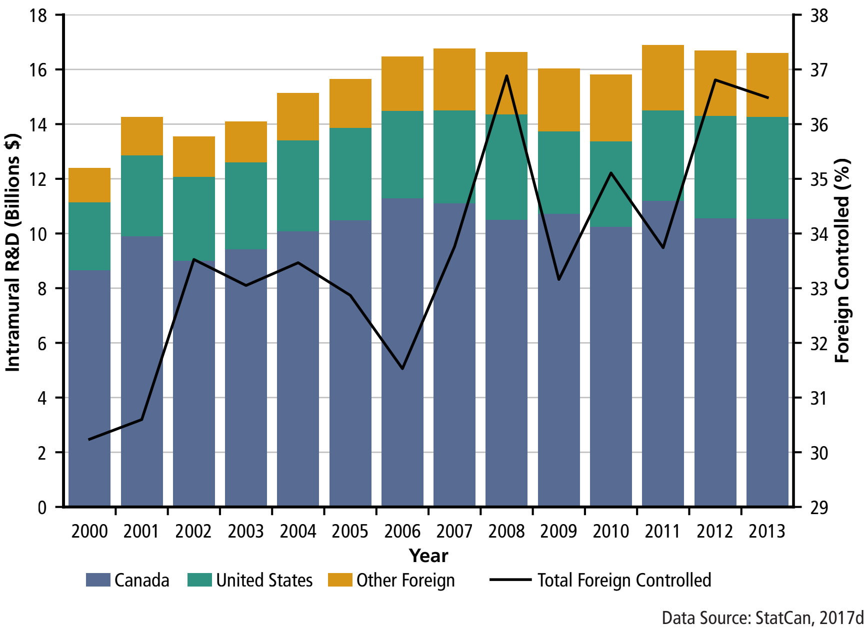


Figure 4.6

In-House Industrial R&D Expenditures by Country of Control, 2000–2013

Between 30 and 37% of Canada's in-house industrial R&D expenditures are typically controlled by foreign firms. As of 2013, this equalled over $6 billion in R&D expenditures, of which the United States accounted for $3.7 billion.

4.2 INDUSTRIAL R&D OUTPUTS: PATENTS, TRADEMARKS, AND DESIGNS

4.2.1 National Outputs

As outlined in Chapter 3, basic research output can be approximated with bibliometric analysis. However, output from applied research is more complicated to capture. Being closer to market, applied research is less likely to be published in journals (Stephan, 2010; CCA, 2013b). Research with potential revenues is often protected by IP mechanisms such as patents, trademarks, integrated circuit topography, plant breeders' rights, know-how, trade secrets, or industrial designs. A Statistics Canada survey on IP management found the most popular forms of IP protection across all industries to be domain names (43%) and non-disclosure agreements (26%) (StatCan, 2012c). Patents, held or used by only 5% of companies, were among the least popular. Different types of IP protection can vary widely in the level or degree of protection that they provide, in their formal legal status, and in the time and resources required to produce them (Jaffe & Lerner, 2006).

The World Intellectual Property Organization (WIPO) gathers IP data from national and regional IP offices, international filing, and the PATSTAT database maintained at the European Patent Office (WIPO, 2017). Table 4.3 presents the global share and per capita production and rank for patents, trademarks, and designs. Canada's share of patent applications is 1% of the world's total. In per capita terms, Canada ranks 18th and is outperformed by Japan, South Korea, and many European countries such as Finland, Sweden, and Switzerland. Canada ranks 34th with 0.9% of trademark applications and 34th with 0.5% of industrial design applications. Switzerland ranks first in patents, trademarks, and designs.

To get a more comprehensive picture of industrial patenting, the Panel analyzed data from the United States Patent and Trademark Office (USPTO) where Canadian firms file most of their patents.[39] Between 2003 and 2014, the private sector was by far the greatest contributor to patents in Canada, representing about 90% of Canadian patents granted by the USPTO. The largest producers of patents in the private sector between 2009 and 2014 were BlackBerry (5,166) and Nortel Networks (605). In 2014, more than half of all patents issued were to BlackBerry. Although academia is a minor contributor to

39 Although no single patent office covers all patents registered worldwide, the USPTO is one of the largest registries of patented inventions in the world. USPTO data were retrieved from PATSTAT. The technology classification used in this report is the WIPO, which links International Patent Classification (IPC) symbols, a widely used system around the world, to 35 fields of technology. The United States and Canada have a clear advantage in international comparisons using the USPTO because firms from both countries tend to file patents disproportionally at the USPTO.

Table 4.3

Patents, Trademarks, and Design Applications by Share, Per Capita, and Rank, Selected Countries, 2010–2015

Country of Origin	Patents			Trademarks			Industrial Designs		
	Share (%)	Per capita (x100)	Rank	Share (%)	Per capita (x100)	Rank	Share (%)	Per capita (x100)	Rank
Switzerland	1.7	3.09	1	2.3	11.70	1	2.5	2.63	1
South Korea	8.4	2.47	2	2.6	2.13	20	5.8	0.99	4
Japan	18.9	2.23	3	3.0	1.00	36	4.9	0.33	22
Finland	0.5	1.42	4	0.5	4.04	10	0.6	0.96	6
Sweden	0.9	1.40	5	1.2	5.13	5	1.3	1.15	3
Germany	7.2	1.31	6	9.4	4.86	7	8.0	0.85	8
Denmark	0.5	1.25	7	0.7	5.10	6	0.9	1.38	2
Netherlands	1.4	1.23	8	2.4	5.89	4	1.8	0.91	7
United States	19.3	0.90	9	12.0	1.58	27	6.7	0.18	30
Israel	0.5	0.89	10	0.2	1.05	33	0.3	0.35	20
Austria	0.5	0.88	11	1.3	6.38	3	1.0	0.99	5
Norway	0.2	0.66	12	0.2	1.85	24	0.2	0.36	18
Belgium	0.5	0.64	13	1.1	4.06	9	0.8	0.60	10
France	2.8	0.63	14	4.8	3.05	14	4.5	0.58	11
Ireland	0.2	0.58	15	0.5	4.09	8	0.2	0.33	23
Singapore	0.2	0.56	16	0.3	2.22	19	0.2	0.26	26
United Kingdom	2.1	0.48	17	5.3	3.45	13	3.6	0.48	15
Canada	1.0	0.42	18	0.9	1.05	34	0.5	0.13	34
New Zealand	0.1	0.42	19	0.3	2.37	18	0.1	0.24	28
Australia	0.5	0.30	20	1.2	2.08	21	0.6	0.21	29
China	25.9	0.28	21	19.4	0.60	44	39.7	0.25	27
Italy	1.1	0.27	22	4.2	2.95	15	3.9	0.56	12

Data Source: WIPO (2017) and Panel calculations

The table provides data on the production of IP for the 22 countries over 1,000,000 inhabitants that produce the most patents per capita. It includes the global share, global rank, and per capita amount of patents, trademarks, and design applications. Canada performs poorly on these three indicators. Total applications by applicant's origin were retrieved from the WIPO database.

patents overall in Canada (under 10%), its contribution is significant in fields such as Biotechnology, Pharmaceuticals, and Analysis of Biological Materials. Governmental applied research is particularly active in the technical fields of Biotechnology, Food Chemistry, and Basic Materials Chemistry. This reflects the distinct patterns of patenting activity found among performers. For instance, whereas the private sector generally focuses on patenting technologies that are poised for commercialization, universities tend to produce more science-based patents that may not yet be ready for commercialization (Greenspon & Rodigues, 2017). See Tables C.1, C.2, C.3, C.4, C.5 and Figure C.1 in the appendix for additional data on patents.

4.2.2 Research Patents by Industry

The preferred form of IP protection varies by industry. Although BlackBerry and Nortel produced the most patents in Canada, open source is used more frequently overall in the software (19% of those surveyed by Statistics Canada) and ICT (12%) industries. Rather, patents are more frequently used by life sciences (29%) and pharmaceutical (24%) firms. Trademarks are even more common in pharmaceutical (40%) and chemical (39%)manufacturing. Other industries, such as mining, rarely use any form of IP protection (StatCan, 2012a, 2012b, 2012e). Because of this, the Panel recognizes that technometric analysis provides a very incomplete (and potentially distorted) picture of IP activity. However, although patents are costly to file, they often have the potential to generate significant revenues (Jaffe & Lerner, 2006). Patents thus provide a decidedly limited, but nevertheless insightful, indication of strengths in areas of R&D where the application of research is the primary aim, at least for some industries in some countries.

Despite weak performance in patenting, Canada excels in some technical fields. Its highest shares of patents are in the fields of Civil Engineering (4.2% of world patents granted by the USPTO), Digital Communication (3.5%), and Other Special Machines (3.2%). The share of Canadian patents decreased in 28 technical fields (including in the top 3) and increased in 7 between the 2003–2008 and 2009–2014 periods (Table C.1 in the appendix). This can partially be explained by the dramatic increase of patents issued at the USPTO to China (over 200% between 2003 and 2014, calculated with fractional counts). Computer Technology (3,777 patents), Digital Communication (2,617), and Telecommunications (2,108) are the technical fields with the greatest number of patents issued to Canada (fractional count, 2009–2014). The technical fields with the highest growth for the 2003–2014 period are IT Methods for Management (GR = 3.0) and Computer Technology (GR = 3.0), while Optics (GR = 0.7) and Thermal Processes and Apparatus (GR = 0.7) have the lowest growth rates (Table C.2 in the appendix).

4.2.3 Patent Flow

Over the past decade, the Canadian patent flow in all technical sectors has consistently decreased. Patent flow provides a partial picture of how patents in Canada are exploited. A negative flow represents a deficit of patented inventions owned by Canadian assignees versus the number of patented inventions created by Canadian inventors. The patent flow for all Canadian patents decreased from about −0.04 in 2003 to −0.26 in 2014 (Figure 4.7). This means that there is an overall deficit of 26% of patent ownership in Canada. In other words, fewer patents were owned by Canadian institutions than were invented in Canada. This is a significant change from 2003 when the deficit was only 4%.

The drop is consistent across all technical sectors in the past 10 years, with Mechanical Engineering falling the least, and Electrical Engineering the most (Figure 4.7). At the technical field level, the patent flow dropped significantly in Digital Communication and Telecommunications. For example, the Digital Communication patent flow fell from 0.6 in 2003 to −0.2 in 2014. This fall could be partially linked to Nortel's US$4.5 billion patent sale to the Rockstar consortium (which included Apple, BlackBerry, Ericsson, Microsoft, and Sony) (Brickley, 2011). Food Chemistry and Microstructural and Nanotechnology both also showed a significant drop in patent flow.

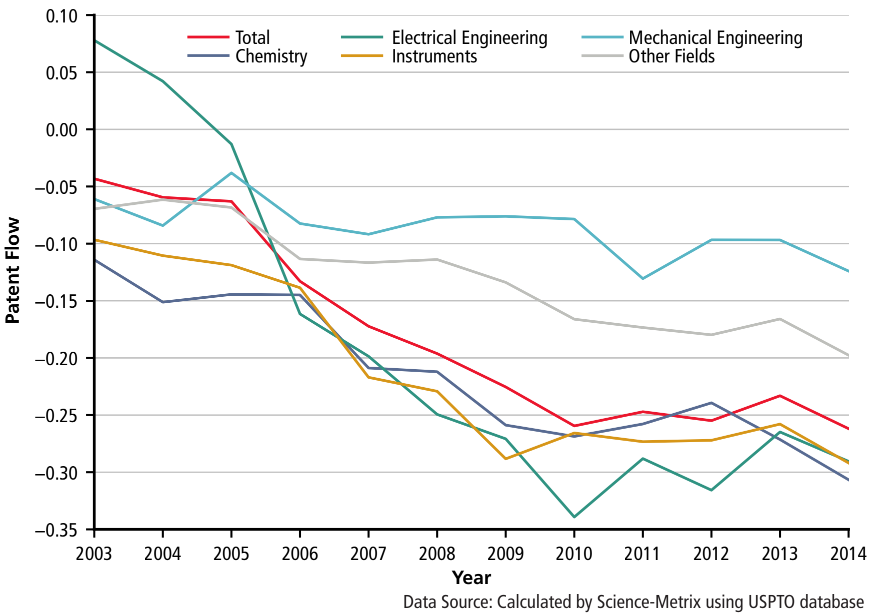


Figure 4.7

Canadian Patent Flow for all Technical Sectors, 2003–2014

The figure plots patent flow for the five major technical sectors between 2003 and 2014. See Figure C.1 and Table C.2 in the appendix for additional data on patent flow.

The factors underlying Canada's increasingly negative patent flow are complex. A foreign company may have purchased a patent or the research may have been undertaken in Canada by an employee of a foreign company. For example, a 2011 study of Canadian patent flow in the nanotechnology industry found that approximately half of all Canadian-invented nanotechnology patents were owned by foreign assignees (Beaudry & Schiffauerova, 2011). In fact, nearly one-third of nanotechnology patents by Canadian inventors came from employees of XRCC, Xerox's Canadian research centre. Thus, the R&D activities that led to these Canadian-invented patents were largely funded by a U.S. firm (Xerox Corporation, USA), of which those Canadian inventors were employees (Beaudry & Schiffauerova, 2011).

4.3 CANADA'S INDUSTRIAL R&D STRENGTHS

The Panel measured industrial R&D strengths in much the same way as it measured industrial R&D spending across countries: by magnitude, intensity, and growth. Table 4.4 presents data on industrial R&D spending across leading and lagging industries. The first table ranks Canadian industries according to a composite indicator based on these three dimensions for the 2006–2015 period. The second table reports their R&D spending magnitude and growth between 2014 and 2017, using the latest available data.[40]

Between 2011 and 2015, seven Canadian industries invested, on average, more than $1 billion per year in R&D: scientific R&D services, computer systems design, communications equipment manufacturing, aerospace manufacturing, information and cultural industries, wholesale trade, and oil and gas extraction (StatCan, 2017c, 2017o).[41] Collectively, these seven industries accounted for more than 60% of Canada's industrial R&D. With respect to intensity, only 10 of Canada's 45 industries invested more than 5% of their revenue in R&D between 2009 and 2013 including in scientific R&D services (30.1% of revenue), communications equipment manufacturing (17.3%), computer systems design (8.1%), and aerospace manufacturing (5.6%) (StatCan, 2017a).

40 Note that R&D spending data for the year 2016 are preliminary, and data for 2017 are intentions reported by firms.

41 These refer respectively to the following NAICS industries 5417, 5415, 3364, 51, 41, 10, and 3342. In what follows, the following short-hands are used: pharmaceutical manufacturing equals pharmaceutical and medicine manufacturing; aerospace manufacturing equals aerospace products and parts manufacturing; telecommunications services equals telecommunications and data processing, hosting, and related services; and automotive manufacturing equals motor vehicle and parts manufacturing.

Table 4.4

Industrial R&D Strengths, Top and Bottom 10 Canadian Industries, 2006–2015

	2011–2015 Magnitude (Millions $)	2006–2015 Growth (%)	2009–2013 Intensity (%)	2006–2015 Strength
Top 10 Industries				
Scientific research and development services	2,050	6.63	30.10	254.17
Computer systems design and related services	1,619	3.35	8.08	152.28
Communications equipment manufacturing	1,158	–1.67	17.33	148.60
Aerospace products and parts manufacturing	1,509	5.55	5.60	143.81
Information and cultural industries	1,477	5.50	2.78	132.79
Wholesale trade	1,450	7.43	1.58	132.02
Oil and gas extraction, contract drilling and related services	1,287	3.61	0.93	112.85
Primary metal (ferrous) manufacturing	117	26.04	0.30	106.68
All other transportation equipment manufacturing	175	15.81	2.38	92.26
Navigational, measuring, medical and control instrument manufacturing	407	–0.40	8.22	84.73
Bottom 10 Industries				
Wood product manufacturing	80	–4.41	0.90	34.97
Non-metallic mineral product manufacturing	62	–5.66	0.76	30.70
Furniture and related product manufacturing	30	–6.20	1.00	28.66
Motor vehicle and parts manufacturing	238	–12.44	0.36	21.90
Rubber product manufacturing	20	–8.23	0.38	21.31
Petroleum and coal products manufacturing	92	–16.30	4.87	20.67
Textile mills and textile product mills	33	–10.83	1.80	20.52
Beverage and tobacco product manufacturing	11	–8.92	0.63	20.08
Paper manufacturing	156	–12.49	0.90	19.61
Forestry, logging and support activities for forestry	9	–15.80	1.00	4.95

This section of the table presents domestic (NAICS) industrial R&D data for 20 Canadian industries on three dimensions: magnitude (average annual BERD for 2011 to 2015 in current dollars), intensity (average annual BERD intensity for 2009 to 2013), and growth (compound annual growth rate for 2006 to 2015). The composite indicator, which weights the three dimensions equally, is presented in the final column. Based on this indicator, the top table includes the top and bottom 10 industries of R&D. Cells that are shaded green, blue, and yellow correspond to: magnitude (> $1 billion), growth (> 2.6%), and intensity (> 5%), respectively. Orange cells indicate the four industries of R&D strength. For aerospace products and parts manufacturing, R&D intensity is estimated based on data from 2004 to 2009 (later data are suppressed). CAGR are sometimes calculated for shorter periods, owing to data availability (Table D.3 in the appendix).

continued on next page

	2014–2017	
	Magnitude (Millions $)	Growth (%)
Top 10 Industries		
Scientific research and development services	2,248	1.55
Computer systems design and related services	2,035	–0.30
Communications equipment manufacturing	326	–9.13
Aerospace products and parts manufacturing	1,511	–4.70
Software publishers	1,250	–12.26
Telecommunications and data processing, hosting and related services	697	12.83
Machinery, equipment and supplies merchant wholesalers	963	1.55
Pharmaceuticals and pharmacy supplies merchant wholesalers	311	–5.46
Oil and gas extraction	867	–28.40
Primary metal (ferrous) manufacturing	224	–21.72
All other transportation equipment manufacturing	220	0.45
Navigational, measuring, medical and control instrument manufacturing	390	–0.64
Bottom 10 Industries		
Wood product manufacturing	73	3.13
Non-metallic mineral product manufacturing	44	3.39
Furniture and related product manufacturing	32	–3.13
Motor vehicle and parts manufacturing	214	0.16
Rubber product manufacturing	17	–3.85
Petroleum and coal products manufacturing	–	–
Textile mills and textile product mills	27	20.83
Beverage and tobacco product manufacturing	9	0.00
Paper manufacturing	144	–19.80
Forestry, logging and support activities for forestry	6	–16.67

Data Source: StatCan (2017a, 2017c, 2017o) and Panel calculations

This section of the table reports spending magnitude and growth between 2014 and 2017. Software publishing and telecommunications services are the two largest sub-industries of information and cultural industries, and machinery and equipment wholesale and pharmaceuticals wholesale are the two largest sub-industries of wholesale trade. This helpful decomposition is only available in recent Statistics Canada data. This demonstrates an erosion in industrial R&D spending with significant fluctuations across industries.

The most recent data from Statistics Canada suggests further erosion in R&D spending (StatCan, 2017c). Between 2014 and 2017, Canadian business R&D is projected to further decline by 2.8% per year (in nominal terms) with more than half of this decline coming from oil and gas extraction and software publishing. In this period, only four industries are expected to invest more than $1 billion per year on average in R&D: scientific R&D services, computer systems design, aerospace manufacturing, and software publishing. Among the largest industries,[42] only six are expected to increase their spending on R&D, led by chemical manufacturing (15%), telecommunications services (13%), followed by finance, pharmaceutical manufacturing, scientific R&D services, and machinery wholesale. Most Canadian industries are now spending less on R&D than in the previous decade.

4.3.1 Scientific R&D Services, ICT, and Aerospace – Industries of R&D Strength

The Panel relied on three indicators to identify industries of R&D strength: magnitude (annual average R&D expenditures between 2006 and 2015), intensity (R&D expenditures as a share of revenues between 2009 and 2013), and growth (the compound annual growth rate for the period 2006–2015). Based on this composite indicator (Figure 4.8, Table 4.4), the Panel classified four industries of R&D strength:

- Scientific research and development services
- Computer systems design
- Communications equipment manufacturing
- Aerospace products and parts manufacturing

R&D investment in the scientific R&D services industry is projected to grow during the 2014–2017 period. This industry has accounted for over 5% of Canada's industrial R&D investment since 2006 — investing at a rate that compares well with the G7 average (Table 4.5). But it is not clear what R&D is measured in this industry. Firms in this industry conduct basic research, applied research, and experimental development across all fields of natural science, engineering, and life science (StatCan, 2016e). That is, they use scientific research to develop their products and processes. The classification description lists numerous fields of science as diverse as chemistry, mathematics, and oceanography (StatCan, 2016e). It includes start-ups which are pre-commercial and therefore do not have revenue streams that allow them to be classified by their main commercial product (Lonmo, 2007; CCA, 2013b; Richards *et al.*, 2017). In principle, this could include firms that operate in biotechnology, clean technology, ICT,

42 This includes 16 industries that spent more than $250 million, on average, between 2014 and 2017.

and other scientifically intensive industries. NAICS, ISIC and other industry classifications, however, often single out biotechnology as a core field (Murphy, 2011). Ultimately, whether comprised of bio-tech or other high-tech firms, the strength of this industry may signal promise in Canada's start-ups, and its R&D talent and infrastructure more generally. Unfortunately, these classification systems do not allow for more concrete statements.

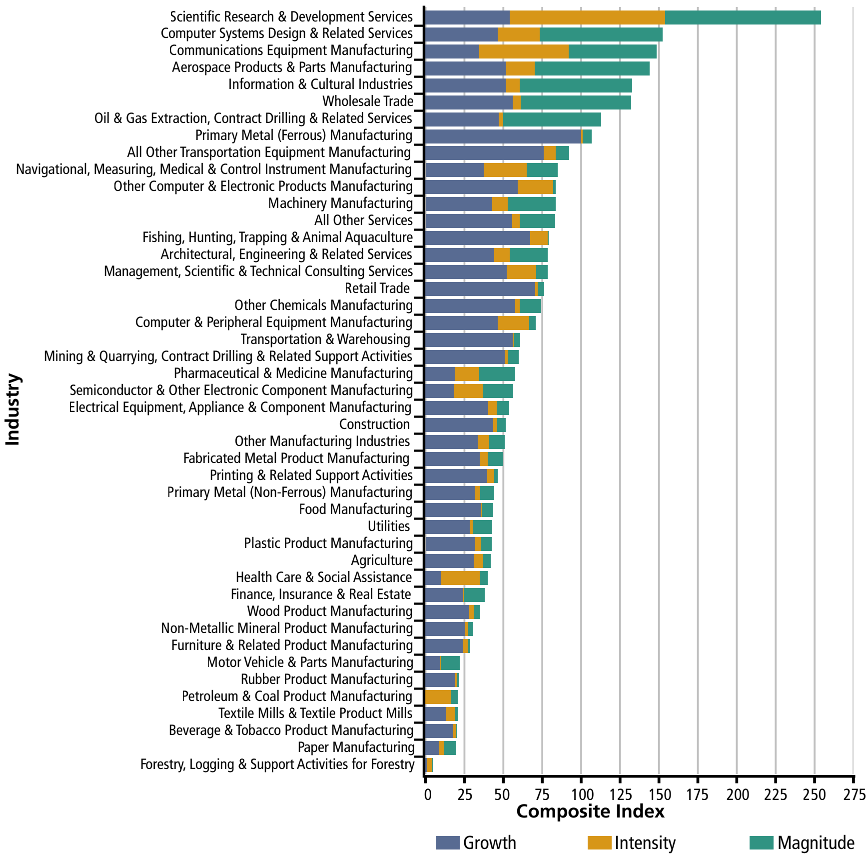
R&D spending trends for computer systems design and communications equipment manufacturing highlight the shift of the economy from manufacturing towards services. While R&D spending in computer systems design[43] — Canada's second largest and fourth most intensive industry — is expected to decline slightly (0.3%) during the 2014–2017 period, it grew at an average rate of 3.4% per year between 2006 and 2015. R&D investment in communications equipment manufacturing, however, is projected to decline by an average of 9.1% per year between 2014 and 2017, and declined by 1.7% per year between 2006 and 2015. Recent data (StatCan, 2017c) also highlights divergent growth between telecommunications services and software publishing as noted above.[44] Ultimately, the performance of the 11 industries that comprise ICT vary considerably. But such granular data permit, among other things, the separation of systems design and telecommunications services from equipment manufacturing and software. Section 4.4.1 provides a profile of the Canadian ICT in recent years.

Despite a projected decrease of R&D investment of 4.7% per year between 2014 and 2017, aerospace manufacturing[45] remains among the largest and most R&D-intensive industries of the Canadian economy (Table 4.4 and Section 4.4.2). However, in 2011, Canadian R&D intensity in aerospace was only two-thirds of the G7 average (Table 4.5). Compared with the 2013 Industrial R&D report (CCA, 2013b), pharmaceutical manufacturing and oil and gas extraction are not considered areas of industrial research strength in this report. See Sections 4.4.3 and 4.4.4, respectively.

43 It includes sectors of the industry such as computer services like custom systems and software, data management, webpage development, and video games (StatCan, 2016e).

44 Similarly, wholesale investment in R&D is decomposed into machinery and equipment, which includes computers and computer equipment, medical devices, navigational equipment, and industrial equipment (e.g., agriculture, forestry, mining), and pharmaceutical wholesale (see Section 1.4.3) (StatCan, 2016e).

45 In addition to aircraft, this industry also produces spacecraft, simulators, satellites, and other sophisticated products (StatCan, 2016e).



Data Source: StatCan, 2017a, 2017i

Figure 4.8

Domestic Industrial R&D Strength, Canadian Industries, 2006–2015

The figure ranks Canadian industries based on a composite index of industrial R&D spending: magnitude (BERD spending, average 2011–2015), intensity (BERD/GDP, average 2009–2013), and growth (BERD CAGR, 2006–2015). Each component is adjusted as a fraction of 100, implying a maximum score of 300.

4.3.2 International Comparison

Comparing Canadian industries to each other reveals where industrial R&D spending is the strongest *within* Canada. Comparing these industries to their international counterparts provides an indication of where Canada may be a world leader. Unfortunately, both data availability and comparability make such comparisons difficult. First, industrial R&D intensity data are only available up to 2011 (Galindo-Rueda & Verger, 2016) and spending data are unavailable for some industries in some OECD countries. For example, internationally comparable spending data are unavailable for Canadian aerospace manufacturing and petroleum refining. Similarly, the Panel notes that services sector data are insufficiently granular, relying on older definitions (e.g., software is increasingly a service) or combining industries that should be separated (e.g., finance and insurance). Second, Statistics Canada and the OECD report R&D spending data according to NAICS and ISIC (Rev. 4) industry classifications, respectively. For some industries, these classifications match either exactly (e.g., scientific R&D, aerospace) or closely (e.g., oil and gas extraction); however, for other industries, such as ICT (e.g., computer systems versus software), information and cultural industries, and health care and social assistance, it is more difficult to make comparisons. Moreover, ISIC (Rev. 4) data are only available for the 2009–2013 period, which provides a shorter period to calculate spending growth.

Canada excels in the scientific R&D services industry. Regardless of its composition, this industry is more intensive in Canada than the G7 average (Table 4.5). While investment was only 25% of the G7 average, Canada was the only G7 country in which R&D spending did not decline between 2009 and 2013. The strong performance of this industry, which likely includes start-ups and biotechnology firms, points to a key Canadian challenge: translating innovation into wealth creation. This may have more to do with managerial talent (and other barriers) than with the innovative ability of Canada's best minds (Section 6.3.6).

These data also suggest that communications equipment manufacturing, which includes telecommunications, was more R&D intensive in Canada than the G7 average. Yet, along with software publishing, communications equipment manufacturing was a small fraction of the G7 average between 2009 and 2013. In 2011, Canadian R&D intensity in aerospace manufacturing was just over 60% of the G7 average.

Canada's performance in pharmaceutical and motor vehicle manufacturing industries was weak by international standards. Both industries invested much less than the G7 average between 2009 and 2013. While R&D intensity in the pharmaceutical industry was about half the G7 average (12.9% versus 28.0%), it was only about 10% of the OECD average in the automotive industry (15.5% versus 1.8%). Oil and gas extraction and paper manufacturing were about as intense as their G7 counterparts.

Table 4.5

International Comparisons of Selected Canadian Industries, 2009–2013

Industry (ISIC Rev.4)	BERD 2009–2013 (Billions $)		Intensity 2011 (%)		Growth 2009–2013 (%)	
	CAN	G7	CAN	G7	CAN	G7
Scientific research and development	1.4	5.5	35.5	30.4	0.1	–1.7
Manufacture of computer, electronic and optical product	1.7	17.8	33.2	24.1	–5.5	1.1
Software publishing	0.4	8.7	–	28.9	–0.1	8.5
Manufacture of air and spacecraft and related machinery	1.3[E]	5.8	20.1	31.7	6.6 [E]	3.9
Manufacture of pharmaceutical, medical, chemical and botanical products	0.3	11.7	12.9	28.0	–13.9	1.0
Mining and quarrying (includes oil and gas extraction)	1.1	0.7	0.8	0.8	11.8	–6.1
Paper manufacturing	0.1	0.2	1.7	1.6	11.9	2.0
Manufacture of motor vehicle	0.1	11.8	1.8	15.5	–12.4	7.3

Data Source: OECD (2017a) and Panel calculations

The table presents international (ISIC Rev. 4) R&D data for Canada's industries of R&D strength and weakness on three dimensions: magnitude (average annual BERD for 2009 to 2013), intensity (BERD intensity in 2011, in U.S. dollars adjusted for purchasing power parity), and growth (compound annual growth rate for 2009–2013). Green, yellow, and blue cells indicate that the Canadian industry exceeds the G7 average for that indicator. Air and spacecraft manufacturing spending and growth is estimated (E) from Table 4.4 above.

Based on the composite indicator (magnitude, intensity, and growth), Table 4.6 highlights 20 industries in which Canada compared well or poorly with the G7 average between 2009 and 2013. In addition to those discussed, Canada compares favourably in cultural industries (book publishing, motion picture and television production), wholesale trade, and real estate, but lags behind in information services (data processing) and in manufacturing chemicals, medical instruments, and food. Reflecting technology sector spending overall (recall Table 4.2), the pattern in Table 4.6 is clear: Canada's internationally leading R&D industries are concentrated in low and medium-low tech sectors (9 of the top 10). Similarly, lagging industries are concentrated in high and medium-high tech sectors (6 of the bottom 10).

It is incontrovertible that Canadian industrial R&D spending is declining and concentrated in industries that are intrinsically less R&D intensive than others. However, the Panel notes that the raw data on R&D spending may not fully reflect the underlying technological, economic, or organizational trends that are influencing the pattern of R&D spending in these industries. The industry profiles in the next section provide some of this perspective.

Table 4.6

International Industrial R&D Comparisons, Top and Bottom 10 Canadian Industries, 2009–2013

Industry (ISIC)	Tech Sector	BERD 2009–2013 (Millions $)	Intensity 2011 (%)	Growth 2009–2013 (%)	Composite Indicator
Top 10 Industries					
5-9: Mining and quarrying	M-L	1,223	0.76	11.80	253
581: Publishing of books, periodicals, and other publishing activities	M-L	46	–	18.35	153
59-60: Motion picture, video, television programme production; programming and broadcasting activities	L	32	0.45	17.05	135
45-47: Wholesale and retail trade; repair of motor vehicles and motorcycles	L	1,081	0.78	–1.23	101
68: Real estate activities	L	6	0.03	–9.31	43
72: Scientific research and development	H	1,416	35.52	0.06	42
16: Manufacture of wood and of products of wood and cork, except furniture	M-L	70	1.34	–5.30	36
94-99: Other service activities, activities of households as employers and of extraterritorial organisations and bodies	L	14	0.11	8.26	21
17: Manufacture of paper and paper products	M-L	104	1.66	11.84	18
77-82: Administrative and support service activities	L	113	0.38	–1.10	4

continued on next page

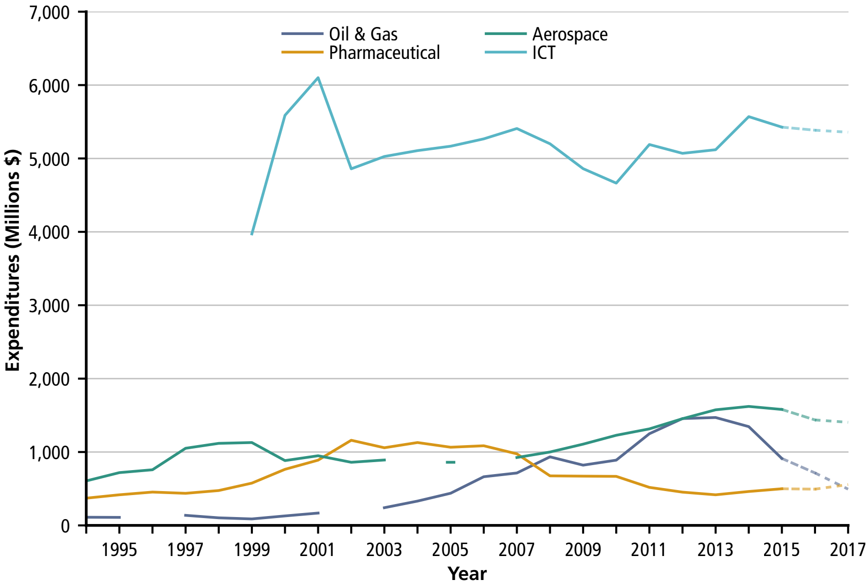
Industry (ISIC)	Tech Sector	BERD 2009–2013 (Millions $)	Intensity 2011 (%)	Growth 2009–2013 (%)	Composite Indicator
Bottom 10 Industries					
41-43: Construction	L	52	0.11	–17.59	–181
22: Manufacture of rubber and plastic products	M	–	1.95	–	–182
31: Manufacture of furniture	M-L	16	0.75	–20.44	–183
10-12: Manufacture of food products; beverages and tobacco products	M-L	124	0.56	–7.53	–192
21: Manufacture of basic pharmaceutical products and pharmaceutical preparations	H	311	12.91	–13.88	–205
325: Manufacture of medical and dental instruments and supplies	M-H	45	3.38	–3.40	–211
20: Manufacture of chemicals and chemical products	M-H	137	2.27	–13.91	–231
55-56: Accommodation and food service activities	L	2	–	–25.67	–231
63: Information service activities	M-H	88	–	10.51	–283
29: Manufacture of motor vehicles, trailers and semi-trailers	M-H	124	1.78	–12.37	–357

Data Source: OECD (2017a) and Panel calculations

The table presents international (ISIC Rev. 4) industrial R&D data for Canada's industries of R&D strength and weakness on three dimensions: magnitude (average annual BERD for 2009 to 2013 in US$ million), intensity (BERD intensity in 2011), and growth (compound annual growth rate for 2009–2013). The composite indicator weights the three dimensions equally. Magnitude and growth are the calculated G7 average while intensity is calculated as the log difference between Canada and the G7. Presented in the final column, it is used to rank the top and bottom 10 industries of R&D. The Tech Sector column indicates the OECD technology sector to which the industry belongs (H = High, M-H = Medium-High, M = Medium, M-L = Medium-Low, and L = Low). See Table D.2 in the appendix for the classification of technology sector by industry.

4.4 INDUSTRY PROFILES

The Panel urges some caution in over-interpreting the evidence presented so far, especially when data are out-of-date, unavailable, or incomparable. This is especially true at the industry level. Moreover, aggregate data do not fully capture the dynamics that drive the evolution of industrial R&D. Consequently, the Panel sought to provide a more detailed assessment of the four industries identified in 2013 as areas of relative industrial R&D strength for Canada: ICT, aerospace manufacturing, pharmaceutical manufacturing, and oil and gas extraction. R&D spending in these industries is depicted in Figure 4.9.



Data Source: StatCan, 2017c, 2017o

Figure 4.9

Industrial R&D Expenditures for Selected Industries in Canada, 1994–2017

Among the four industries identified as industrial R&D strengths in Canada (CCA, 2013b), aerospace and oil and gas extraction have experienced consistently increasing R&D investment since the mid-1990s. R&D spending in the pharmaceutical industry increased until the mid-2000s and decreased sharply post-2008. ICT investment has been constant since 1999. Note the sharp decrease of industrial R&D investments in oil and gas extraction, contract drilling and related services in the past five years. Years 1994–2013 are based on the previous Statistics Canada methodology and years 2014–2017 on the new methodology. Caution should be used when interpreting differences between 2013 and 2014 R&D expenditures due to the changes in Statistics Canada's methodology. Data for 2016 are preliminary and 2017 data are intentions reported by firms (dashed lines).

4.4.1 Information and Communication Technologies

Current Status

ICT is the largest industrial investor in R&D. R&D spending in the 11 ICT industries (including computer systems design and telecommunications) are predicted to account for 31% of total Canadian industrial R&D spending in 2017.[46] This dominance of ICT has persisted despite a slight decrease in Canada's share of global research output and a slight decline in the field's share of all Canadian research. ICT researchers in Canada continue to excel in several subfields, including Medical Informatics, Computer Hardware and Architecture, and Networking and Telecommunications. Canada has a long history of applied R&D driven by domestic firms such as Nortel, BlackBerry, and

46 Spending is based on intentions reported by the industry.

subsidiaries of multinational firms such as Xerox and IBM.[47] While ICT industries remain heavily involved in R&D activity, an erosion in research investment in ICT manufacturing, such as semiconductor and communications equipment manufacturing, occurred over 2006–2015 (StatCan, 2017c, 2017o). Investment in computer systems design and telecommunications services, in comparison, have shown growth over the same period. This partially reflects Canada's participation in a global shift from hardware to software development (e.g., the rise of software as a service, or SaaS, models, and software-defined digital networks in telecommunications) and increased outsourcing of semiconductor manufacturing and other hardware to Asia.

Evolution and Opportunities

Several industries are currently on the brink of a technology revolution through ICT-driven innovation. In the manufacturing sector, Industry 4.0 has emerged as a term for an anticipated disruption in industrial processes that is expected to trigger a step change in productivity, similar to that following the invention of the steam engine, electrification, mass production, and computers. The main driver of change is the merging of advanced software solutions with automated production processes to create cyber-physical production systems, also referred to as the digitization of manufacturing or smart industry. ICT innovations, such as the internet of things, AI, cloud computing, big data analysis and virtual reality, combined with additive manufacturing processes, enable intelligent object networking, independent process management, and the interaction between real and virtual worlds (Hermann *et al.*, 2016). These trends create opportunities for Canada to the extent that Canadian ICT firms may be well positioned to provide next-generation networking technologies and related services driving changes in manufacturing.

Advances in ICT extend beyond manufacturing, transforming industries. For example, financial services appears poised for transformation due to the advent of new financial technologies, or FinTech, including blockchain and AI-based applications. In Canada, the financial services industry has recently increased R&D investments to ensure that it is well positioned for upcoming innovations driven by ICT research (Box 4.2). While blue-collar workers in manufacturing were most heavily affected by previous technological revolutions, some emerging technologies now have the potential to have a strong impact on white-collar workers. AI-supported technologies may be able to perform many of the tasks previously performed by service workers in many industries. For example, in Canada, start-up Botler AI is providing a free chatbot to assist immigrants in

47 At their peak in 2000, worldwide R&D expenditures at Nortel were just under $6 billion annually, a figure that remains far greater than that of any Canadian firm today (Re$earch Infosource Inc., 2018).

navigating legal procedures for immigration (Erlick, 2017). Similarly, ROSS Intelligence, with offices in Toronto and San Francisco, uses AI and computers to analyze large volumes of legal documents (Rieti, 2017).

Box 4.2
The FinTech Revolution

Financial services is a key industry in Canada. In 2015, the industry accounted for 4.4% of Canadian jobs and about 7% of Canadian GDP (Burt, 2016). Toronto is the second largest financial services hub in North America and one of the most vibrant research hubs in FinTech. Since 2010, more than 100 start-up companies have been founded in Canada, attracting more than $1 billion in investment (Moffatt, 2016). In 2016 alone, venture-backed investment in Canadian financial technology companies grew by 35% to $137.7 million (Ho, 2017). The Toronto Financial Services Alliance estimates that there are approximately 40,000 ICT specialists working in financial services in Toronto alone.

AI, blockchain, and other results of ICT research provide the basis for several transformative FinTech innovations including, for example, decentralized transaction ledgers, cryptocurrencies (e.g., bitcoin), and AI-based risk assessment and fraud detection. These innovations offer opportunities to develop new markets for established financial services firms, but also provide entry points for technology firms to develop competing service offerings, increasing competition in the financial services industry. In response, many financial services companies are increasing their investments in FinTech companies (Breznitz *et al.*, 2015). By their own account, the big five banks invest more than $1 billion annually in R&D of advanced software solutions, including AI-based innovations (J. Thompson, personal communication, 2016). The banks are also increasingly investing in university research and collaboration with start-up companies. For instance, together with several large insurance and financial management firms, all big five banks have invested in the Vector Institute for Artificial Intelligence (Kolm, 2017).

AI is the ability of machines to make decisions and accomplish complex goals (Tegmark, 2017). Today's AI is mostly narrow, with each system designed to accomplish specific goals such as playing chess or detecting cancer. However, recent advances in language translation, musical composition, and video game playing suggest that much more complex goals can be achieved. AI has enormous potential, but it is uncertain how it will affect labour markets, medicine, transportation, security, conflicts, laws, and other institutions and industries (Bostrom, 2014; Tegmark, 2017).

A precondition for machines making intelligent decisions is their understanding of how the world works — an ability also referred to as deep learning. While research on AI began in the mid-1950s, it did not become a relevant source of scientific output until the mid-1990s. Since 2005, the number of publications referring to neural networks, deep learning, or AI has increased exponentially thanks to growing interest from other fields in developing AI applications (Niu *et al.*, 2016). Today, researchers believe that the field is in the process of achieving major breakthroughs that could enable potentially transformative innovations in several industries, including autonomous vehicles, logistics, automation, medical diagnosis, banking, or recommendation systems.

AI has attracted researchers and funding since the 1960s; however, there were periods of stagnation in the 1970s and 1980s, sometimes referred to as the "AI winter." During this period, the Canadian Institute for Advanced Research (CIFAR), under the direction of Fraser Mustard, started supporting AI research with a decade-long program called Artificial Intelligence, Robotics and Society, which was active from 1983 to 1994. In 2004, a new program called Neural Computation and Adaptive Perception was initiated and renewed twice in 2008 and 2014 under the title, Learning in Machines and Brains. Through these programs, the government provided long-term, predictable support for high-risk research that propelled Canadian researchers to the forefront of global AI development. In the 1990s and early 2000s, Canadian research output and impact on AI were second only to that of the United States (CIFAR, 2016). NSERC has also been an early supporter of AI. According to its searchable grant database, NSERC has given funding to research projects on AI since at least 1991–1992 (the earliest searchable year) (NSERC, 2017a).

The University of Toronto, the University of Alberta, and the Université de Montréal have emerged as international centres for research in neural networks and deep learning, with leading experts such as Geoffrey Hinton and Yoshua Bengio. Recently, these locations have expanded into vibrant hubs for research in AI applications with a diverse mix of specialized research institutes, accelerators, and start-up companies, and growing investment by major international players in AI development, such as Microsoft, Google, and Facebook. Many highly influential AI researchers today are either from Canada or have at some point in their careers worked at a Canadian institution or with Canadian scholars. CIFAR Distinguished Scholar Geoffrey Hinton, who pioneered AI research at the University of Toronto, trained several top leaders in different fields of

AI development, including Yann LeCun (Professor, New York University and Director of AI Research, Facebook); Brendan Frey (Founder and CEO, Deep Genomics); Ruslan Salakhutdinov (Director of AI Research, Apple); Richard Zemel (Co-Founder, Smart Finance); and Ilya Sutskever (Co-Founder and Research Director, OpenAI) (UofT News, 2017b).

As international opportunities in AI research and the ICT industry have grown, many of Canada's AI pioneers have been drawn to research institutions and companies outside of Canada. According to the OECD, Canada's share of patents in AI declined from 2.4% in 2000 to 2005 to 2% in 2010 to 2015. Although Canada is the sixth largest producer of top-cited scientific publications related to machine learning, firms headquartered in Canada accounted for only 0.9% of all AI-related inventions from 2012 to 2014 (OECD, 2017c). Canadian AI researchers, however, remain involved in the core nodes of an expanding international network of AI researchers, most of whom continue to maintain ties with their home institutions. Compared with their international peers, Canadian AI researchers are engaged in international collaborations far more often than would be expected by Canada's level of research output, with Canada ranking fifth in collaboration.

Canada is now taking steps to build on its early leadership in the field. In Budget 2017, the federal government promised $125 million for a Pan-Canadian AI Strategy to promote collaboration among the AI clusters in Montréal, Toronto–Waterloo, and Edmonton, to be administered by CIFAR (GC, 2017). Part of this funding will support the University of Toronto's Vector Institute, which aims to significantly increase student training in Canada and support the development of an AI supercluster in Toronto. In collaboration with other AI hubs in Canada, the Institute seeks to ensure a critical mass of AI research, funding, highly qualified personnel (HQP), and investment in development activities in Canada. This would address one of the main concerns raised by companies investing in AI research in Canada, namely to ensure that sufficient AI expertise will be available in the future to justify the long-term prospects of their investments (i.e., a critical mass of talent). The Institute has secured close to $200 million in funding, approximately half of which was provided by private-sector partners (The Toronto Star, 2017; UofT News, 2017a). In May 2017, the Government of Quebec invested $100 million to support the AI cluster in Montréal, drawing on the expertise developed by the Institute for Data Valorization (IVADO) (UdeM, 2017). Edmonton has also emerged as a nascent hub in AI research with DeepMind (an AI start-up acquired by Google in 2014) recently announcing that it will open an office there due to the area's depth of academic expertise (Simons, 2017).

4.4.2 Aerospace Products and Parts Manufacturing

Current Status

Aerospace products and parts manufacturing is the third largest spender as measured by magnitude, intensity, and growth. In 2016, the industry contributed almost $13 billion in GDP including about $9 billion from manufacturing and $3.9 billion from maintenance, repair, and overhauls. Between 2011 and 2016, aerospace GDP grew by 8% (ISED & AIAC, 2016). While between 2014 and 2017, R&D investment declined 4.7% in the aerospace industry (StatCan, 2017c).

According to the Aerospace Industries Association of Canada (AIAC), aerospace is the only industry other than natural resources where Canada has a clear comparative advantage over other countries (AIAC, 2016). Certainly, technological innovation is a driver of growth in the aerospace sector. In 2017, aerospace products and parts manufacturing was the third largest spender on R&D ($1.51 billion) (Table 4.4). Roughly three-quarters of aerospace firms report having introduced innovations in recent years (OECD, 2015a; STIC, 2015). Yet, R&D intensity in aerospace is just over 60% of the G7 average (Table 4.5).

Rather, Canada's advantage in aerospace may be in its talent. Research in the subfield of Aerospace and Aeronautics is internationally competitive, ranking seventh by ARC and sixth in reputation. However, between 2003 and 2008, and 2009 and 2014, the subfield experienced a 19% decline in publication output. Nonetheless, in 2015 the industry accounted for 89,000 jobs of which 33% of aerospace jobs were in innovation-related occupations, such as engineers, scientists, and technicians. In the space systems subsector, this proportion is close to 60% (ISED 2016).

Evolution and Opportunities

Canada's aerospace industry benefits from a mature innovation ecosystem that includes leading university research institutes, a presence of companies from all industry tiers and institutions, and networks that support collaboration and risk-sharing such as the Consortium for Research and Innovation in Aerospace in Quebec (CRIAQ). CRIAQ was established in 2002 with the support of the Government of Quebec to increase the competitiveness of the industry and enhance the collective knowledge base through improved education and training. By 2015, CRIAQ had completed or initiated more than 100 research projects worth more than $100 million with the participation of 1,000 researchers and 900 students (CRIAQ, 2015). In 2012, the Federal Aerospace Review recommended, among other initiatives, that the federal government fund a "Canada-wide initiative to facilitate communication and collaboration among aerospace companies, researchers and academics" (Emerson *et al.*, 2012).

In response, the Consortium for Aerospace Research and Innovation in Canada (CARIC) was launched in 2014. Modelled in some respects on CRIAQ, CARIC expanded the reach of collaborative opportunities and networks across the country, aiming to facilitate the integration of the entire aerospace value chain across Canada, including areas with low research density and little experience in collaborative research. As one of its early successes, CARIC became the official contact point for the European Union for the co-development of international research projects (CRIAQ, 2015; Prince *et al.*, 2016).

Like other industries, however, aerospace faces evolving competitive pressures and new imperatives arising from shifts in policy, demographics, and industry developments. For example, population growth and urbanization generate increased demand for air travel, but also new demands for environmental protection and noise reduction. The need to mitigate climate change challenges the aerospace industry to find ways to reduce emissions or use renewable fuel sources. In its 2016 white paper on innovation, AIAC (2016) identified four main drivers of change: digitization of manufacturing (Industry 4.0), environmental imperative, consolidation of global supply chains, and autonomous systems.

The aerospace industry remains a dynamic, competitive source of industrial R&D and technological innovation in Canada. As a Canadian high-tech industry with a global profile, Canadian firms, researchers, and research institutions can continue to build on its existing research capacity by taking advantage of emerging opportunities, such as the search for less emissions-intensive fuels and propulsion systems, and the development of autonomous systems for air and space travel. Maintaining Canada's past record of successes in this industry, however, requires more than the status quo in institutional support and funding levels. In the Panel's view, the industry needs new models of risk-sharing that better take into account the complexity of large, multi-year projects with technological, economic, and geopolitical uncertainties. Canadian SMEs also need to be better integrated into domestic and international R&D consortia and markets; there is an ongoing demand for continuous training and retraining of the HQP required by the industry.

4.4.3 Pharmaceutical Manufacturing

Current Status

Between 2006 and 2015, R&D spending in pharmaceutical manufacturing declined (–8.3%), investing at an intensity that was about half the G7 average (12.9% versus 28.0%) in 2011 (Table 4.5). However, between 2014 and 2017, this industry was one of few that increased their R&D investment. By contrast, pharmaceutical wholesale R&D investment declined between 2014 and 2017. When combined with wholesale activities, the Canadian pharmaceutical industry is projected to invest more than $800 million annually between 2014 and 2017 (StatCan, 2017c). The level of business expenditures has changed significantly over the last three decades in response to regulation and market forces. Between 1988 and 2003, research spending grew from around $200 million to almost $1.2 billion, following a commitment from the industry to spend 10% of its sales on research in Canada in exchange for favourable patent legislation (CCA, 2009). After a period of relative stability, research spending began to decline in 2007 as the industry entered a period of transformation. Specifically, in response to declining productivity of research investments, a deterioration of the global financial environment, and increasing pressures from drug price control policies, companies started to consolidate research activities in hubs located outside of Canada. They also shifted therapeutic research, drug discovery, and early-stage clinical development to collaborative networks, engaging new players including universities, start-up companies, and an emerging model of contract research organizations (CROs) (Munos, 2015). GDP and exports also declined between 2009 and 2013, and the industry accounted for only 0.2% of Canada's GDP in 2013 (StatCan, 2018; OEC, n.d.).

Evolution and Opportunities

A different model of public-private investment in Canada seeks to establish new partnerships and integrate existing research infrastructure previously held by pharmaceutical companies. However, it is now at risk of being decommissioned as these companies scale down their Canadian operations (Box 4.3). The investments helped reposition Canadian researchers and institutions within international networks of research institutions, start-ups, and CROs providing research services to larger pharmaceutical companies. In combination with funding for National Centres of Excellence and other research networks, the investments also provided new opportunities for HQP in biopharma, and incentives for continued investments in discovery research by universities and other primary research institutions. Despite some success with this model, Canada appears to be increasingly undertaking contract R&D and exporting patents. However, given that some biotechnology R&D may be captured in scientific R&D services (Section 4.3), it is difficult to make a definitive statement. Nonetheless, pharmaceutical R&D is not a Canadian strength.

Box 4.3
Building a Canadian Niche in Pre-Commercial Drug Discovery R&D Through Investments and Partnerships

Organizations across Canada are now contributing to Canada's widely recognized capabilities in pre-commercial drug discovery and development. In Montréal, the *Centre québécois de développement du médicament* (CQDM) was founded in 2008 with funding from the Government of Quebec, the federal government, and pharmaceutical companies (CQDM, 2017a, 2017b). CQDM provides funding and "neutral ground" for pre-competitive research on potential "breakthrough tools and technologies that enhance biopharmaceutical R&D productivity and accelerate the development of safer and more effective drugs." In 2016, the Centre funded 9 projects and 27 researchers from 12 private and public institutions (CQDM, 2016, 2017b).

Also in Montréal, the NEOMED Institute was founded in 2012 as a joint venture between AstraZeneca, Pfizer, the federal government, and the Government of Quebec, making AstraZeneca's facility available as an open-access drug discovery hub for research on small molecules and translation and commercialization of early products (NEOMED Institute, 2012). In 2015, a second facility for clinical trial serology research on biologics and vaccines was made available by GlaxoSmithKline. In collaboration with GlaxoSmithKline and the Government of Quebec, the NEOMED Institute created NEOMED-LABS, dedicated to clinical trial testing in this facility and maintaining the HQP and expertise left behind by GlaxoSmithKline (NEOMED Institute, 2015). Together, the facilities now host 29 independent businesses with 300 employees. Since its creation, NEOMED has attracted more than $90 million in private and public funding, $50 million of which was dedicated to R&D (NEOMED Institute, 2017a, 2017b).

Home to both the Pan-Provincial Vaccine Enterprise (PREVENT) and VIDO-InterVac, Saskatoon has become a leading centre of vaccine R&D. PREVENT is a Centre of Excellence for the Commercialization of Research focused on accelerating vaccine development addressing public health needs through pre-clinical and early clinical evaluation. VIDO-InterVac, a research facility for the study of emerging and re-emerging infectious diseases, now hosts "some of the world's most advanced containment level 2 and 3 vaccine research facilities" (VIDO-InterVac, 2017).

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In Vancouver, the Centre for Drug Research and Development (CDRD) has proved effective at accelerating drug development and the translation of Canadian research into therapeutic advances. By helping to validate, de-risk, and advance innovative technologies since its creation in 2007, the CDRD has been involved in out-licensing 14 technologies to the private sector and creating 7 spin-off companies (CDRD, 2017).

Collectively, these types of organizations, along with others such as Accel-Rx in Vancouver and MaRS Health in Toronto have helped maintain Canada's R&D capabilities in niche areas of biopharmaceutical R&D despite an overall outflow of investment and activity (Accel-Rx, 2017; MaRS, 2017).

4.4.4 Oil and Gas Extraction

Current Status

With the expansion of oil production in the Alberta oil sands and in offshore Atlantic platforms in the early 2000s, the oil industry became a significant source of economic activity in Canada. As of 2016, Canada produced approximately 3.8 million barrels of crude oil per day, the majority of which was exported to the United States. Crude oil exports were $128 billion in 2014, and represented nearly one-third of Canada's exports by value (CAPP, 2017). The industry accounted for over 57,000 direct jobs in Canada as of 2016 (StatCan, 2017n). While production has declined since 2014, projections suggest that Canadian crude oil production will increase by about 40% by 2030, to 5.4 million barrels per day (CAPP, 2017). While at a low intensity, between 2006 and 2013, R&D investment in the oil and gas industry increased about 12% per year, reaching a peak of $1.47 billion in 2013. But based on spending intentions reported by firms in the industry, investment is expected to decline by about 30% per year between 2014 and 2017 alongside the retrenchment in global oil prices (StatCan, 2017c). Finally, the innovation survey data also reveal that firms in this industry are less apt to report introducing innovations: only 38% of firms reported having done so, compared with the economy-wide average of 55% (OECD, 2015a).

Evolution and Opportunities

The oil and gas industry is facing multiple pressures, ranging from the recent decline in global commodity prices, increasing environmental pressure, and regulations forcing the industry to look towards innovation as a way to make a step change in productivity. Technological advancements in clean energy and bio-based products could lead to the rise of new substitutes for petroleum products. A transition towards electric or hydrogen-powered vehicles, for example, could affect long-term demand for hydrocarbon energy sources;

however, at this point it is unclear when and at what scale such impacts will occur (CCA, 2015b). Advances in ICT, on the other hand, provide opportunities to develop new, more efficient business models and processes for mining and energy extraction. In short, analysts suggest that the industry "must innovate to survive" (Swart & Granger, 2015; Swart & Otremba, 2016).

Oil and gas exploration in Canada has a legacy of achieving major breakthroughs in technology development when collaborative research is facilitated through government funding or regulation (AI-EES, 2014; COSIA, 2016; ERA, 2017). For example, in 2013, the Canadian Oil Sands Innovation Alliance (COSIA) was launched as a partnership of 13 companies to "accelerate the pace of improvement in environmental performance in Canada's oil sands through collaborative action and innovation" (COSIA, 2016). COSIA seeks to bring together academia, government, and industry to share and jointly develop technologies that reduce the environmental impact of oil sands production. In 2016, COSIA reported that its members had shared 936 distinct technologies and innovations that cost $1.33 billion to develop (COSIA, 2016). Increasing pressure for transformational innovation could give rise to another period of collaborative research that builds on past and current initiatives.

Increasing environmental pressures have led to policies designed to support the development of technology to reduce greenhouse gas emissions (GHGs) (CCA, 2015b). The Government of Alberta established a Specified Gas Emitters Regulation in 2007, which obliges large emitters to reduce their emissions, buy offsets, or pay a fee for every tonne of carbon dioxide emitted above their target level into a clean development fund. Initiatives such as the Future Energy Systems Research Initiative (FESRI) of the University of Alberta and the University of Calgary's Global Research Initiative in Sustainable Low Carbon Unconventional Resources support research and innovation in the clean technology sector, including clean energy sources. The link to clean technology research could allow for increased collaboration not only within the mining and oil and gas sector, but also across sectors and disciplines, leading to a better integration of research on hydrocarbon-based fuels into the broader research landscape on clean technology and sustainable energy (CCA, 2015b).

Pressure to innovate in mining and oil and gas companies, combined with funding initiatives that emphasize research for the reduction of the environmental impact from unconventional oil and gas extraction, offers opportunities for researchers from multiple fields. While, in the short run, a large part of such research would focus directly on the challenges of oil and gas exploration, the long-term objective of supporting a clean energy transition in Canada could be expected to shift the research focus onto clean technologies.

4.5 DATA LIMITATIONS

Data limitations continue to prevent the formation of definitive conclusions about Canada's industrial research investment and capacity in some critical respects. While Statistics Canada has refined its survey methodology for collecting data on industrial R&D, data lags still impede international comparisons on key variables such as industrial R&D intensity by industry. It also remains difficult to interpret the nature of the R&D conducted in some industries, such as wholesale trade and scientific R&D services, though the most recent data released from Statistics Canada has begun to provide a more granular picture of these industries. Reported industrial expenditures on R&D also understate the full extent of industrial investment in innovation in Canada, much of which may not be captured. Finally, patents are only one of many relevant outputs of industrial R&D, and robust, widely comparable data on other outputs and impacts is mostly lacking. These are long-standing methodological challenges, some of which are discussed at length in appendix B of the CCA's 2013 industrial R&D report. Statistics Canada's recent methodological changes have resulted in improvements to this data in Canada; however, it remains more difficult to assess Canada's industrial R&D strengths than it is to assess Canada's research strengths given these limitations.

The limitations of technometric data stem largely from their restricted applicability across areas of R&D. Patenting, as a strategy for IP management, is similarly limited in not being equally relevant across industries. Trends in patenting can also reflect commercial pressures unrelated to R&D activities, such as defensive or strategic patenting practices. Finally, taxonomies for assessing patents are not aligned with bibliometric taxonomies, though links can be drawn to research publications through the analysis of patent citations.

4.6 CONCLUSION

Canada is not a world leader in industrial R&D, ranking 33rd among leading countries on an index assessing the magnitude, intensity, and growth of industrial R&D expenditures. Although Canada is the 11th largest spender, its industrial R&D intensity (0.9%) is only half the OECD average and total spending is declining (–0.7%). Compared with other G7 countries, the Canadian portfolio of R&D investment is more concentrated in industries that are intrinsically less R&D intensive than others. Although nearly 50% of Canada's industrial R&D spending is in high and medium-high tech sectors, this is much less than the G7 average (80%). Canadian BERD intensity is also below the OECD average in these sectors, which include industries such as ICT, aerospace, pharmaceuticals, and automotive. The other half of Canadian R&D investment is in low and medium-low technological sectors (including oil and gas and machinery and equipment), a substantially higher share than the G7 average (17%) and at a much higher intensity in some cases. This spending reflects Canada's long-standing industrial structure (with a focus on natural resources) and patterns of economic activity.

Between 2009 and 2013, there was a shift towards industrial R&D performed at larger firms in Canada. Yet, SMEs still perform a greater share of industrial R&D in Canada than in the United States. Investment by foreign-controlled firms in Canada has increased to more than 35% of total R&D investment, with the United States accounting for more than half. This reflects a shift towards MNEs locating some of their R&D operations outside their country of ownership, often in Canada. This may reflect that Canada excels in talent development. It probably also reflects the fact that, while only producing about 1% of the world's patents, Canada is a net exporter of patents, with patent outflow accelerating in Electrical Engineering, Telecommunications, and Digital Communication. It may signal the strength of some Canadian technology industries or a failure of Canadian industry to capitalize more fully on these technologies by growing these ideas into large companies.

Based on a composite indicator of magnitude, intensity, and growth, the Panel classified four industries of R&D strength:
- Scientific research and development services
- Computer systems design
- Communications equipment manufacturing
- Aerospace products and parts manufacturing

Based on comparisons with other G7 countries, the Canadian scientific R&D services industry performs well globally. That this industry includes pre-commercial companies, some of which may be in biotechnology and other high-tech industries, signals the R&D capacity of Canada arising from its promising start-ups and their talent. That some of these companies fail to grow to scale also signals Canada's challenge with translating technological innovation into wealth creation.

Performance in ICT and aerospace manufacturing is mixed. R&D spending in the Canadian ICT industry is relatively low but intense, while spending in aerospace manufacturing is relatively high but less intense than in other G7 countries. Spending is now declining in ICT and aerospace manufacturing. The Canadian ICT industry continues to adapt to an environment where key firms such as BlackBerry play a smaller role. Aerospace manufacturing continues to face steep international competition. The pharmaceutical manufacturing industry lags internationally and oil and gas extraction compares favourably;

however, spending has rebounded in the former and declined sharply in the latter since 2014. The pharmaceutical manufacturing industry has undergone a substantial reorganization and a significant outflow of economic activity from Canada. The oil and gas extraction industry has been operating in the context of reduced oil prices, heightened environmental concerns, and increased competitive pressures. Ultimately, all four are currently buffeted by commercial and economic headwinds, and the position of many of Canada's former corporate R&D leaders is less secure.

At the same time, the evolution of these industries, both globally and within Canada, points to emerging opportunities. Canada is well positioned to benefit from the emergence of Industry 4.0 and the global shift from hardware to software. In this context, Canada's strengths in ICT services such as software development are a distinct asset. The finance industry may be able to build on Canada's past research strengths related to AI to continue to establish a growing FinTech industry in Toronto. The oil and gas industry can look to the successes of past collaborative R&D efforts as it develops new technologies aimed at mitigating environmental impacts. The aerospace industry can build nationally on the institutional arrangements that solidified Montréal's emergence as the locus of a globally competitive aerospace cluster. Finally, despite an overall loss of R&D activity in the biopharmaceutical sector, Canada has developed niche strengths in key areas of pre-commercial R&D. As a result, these industries still represent areas of substantial industrial R&D potential in Canada despite the challenges they face and recent declines in R&D spending.

5

Regional R&D Activity in Canada

5 Regional R&D Activity in Canada

Key Findings

R&D spending patterns are highly variable across provinces.

- R&D investment in Ontario and Quebec is comparable to that of many advanced countries.
- Virtually the entire decline in Canadian R&D spending from 2006 to 2015 occurred in Ontario and Quebec.
- R&D spending is growing more slowly than GDP in most provinces. R&D intensity decreased in all provinces except Nova Scotia and Newfoundland and Labrador between 2005 and 2014.

Ontario, Quebec, British Columbia, and Alberta publications have the highest average and median impact in Canada. There is, however, tremendous research diversity across provinces.

- Between 2009 and 2014, ARC scores improved in all provinces and territories.
- All provinces produce at least twice as many publications as expected in at least 15 academic subfields.
- Larger provinces specialize less than smaller provinces and have higher rates of international collaboration.

All provinces except Prince Edward Island are net exporters of patents.

- Patent output grew in all provinces between 2004 and 2013 except Quebec where ICT and pharmaceutical activity declined.
- This increase in patenting has coincided with an increase in patent exporting. This may reflect increasing foreign investment in R&D-intensive industries with patents flowing to investor countries.
- Patent exports signal the strength of some Canadian technology industries, but also reflect a failure to capitalize more fully on new technologies by growing ideas into large companies.

R&D activity clusters in and around five large cities: Toronto, Montréal, Vancouver, Ottawa, and Calgary.

- The five cities create patents and high-tech companies at nearly twice the rate of other Canadian cities. They also account for half of clusters in the services sector, and many in advanced manufacturing.
- As urban populations expand exponentially, cities are likely to drive innovation and wealth creation at an increasing rate in the future.

continued on next page

Many clusters relate to natural resources and long-standing areas of economic and research strength. Strong connections between academia and industry are often associated with clusters.

- Natural resource clusters have emerged around the location of resources, such as forestry in British Columbia, oil and gas in Alberta, agriculture in Ontario, mining in Quebec, and maritime resources in Atlantic Canada.
- The automotive, plastics, and steel industries have the most individual clusters due to their economic success in Windsor, Hamilton, and Oshawa.
- Advanced manufacturing industries tend to be more concentrated, often located near specialized research universities.

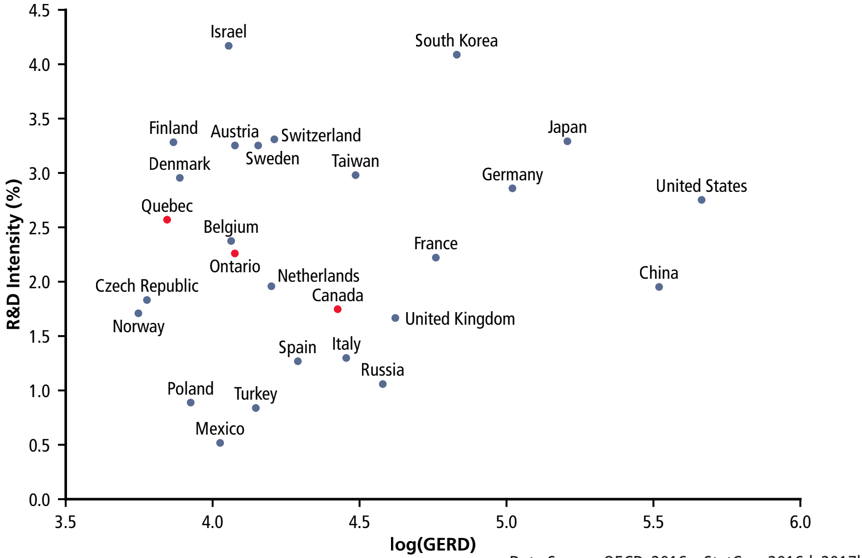
This chapter provides an overview of the regional distribution of R&D activity across Canada. It does so by first surveying R&D investment, publications, and patents across Canadian provinces and territories using recent data from Statistics Canada and other sources. It then builds on this evidence to explore areas of provincial R&D specialization and clusters.

5.1 INVESTMENT BY PROVINCE AND TERRITORY

R&D investment varies widely among advanced economies, reflecting their size, R&D strengths, and industrial structure. As illustrated in Figure 5.1, R&D spending and intensity for these countries can differ by an order of magnitude or a factor of more than two, respectively. In spending and intensity, Quebec and Ontario in fact rival some leading countries, ranking in the top 25 by both measures between 2011 and 2015. Quebec invests more as a percentage of provincial GDP than Ontario (2.6% versus 2.3%),[48] but less overall ($8.5 billion versus $14.6 billion). However, these two provinces lag well behind global leaders such as Israel, South Korea, and Japan in R&D intensity.

R&D spending and intensity varies almost as much among Canadian provinces as it does among the 25 leading countries in Figure 5.1. Ontario and Quebec account for 71% of Canada's R&D spending, investing much more in R&D, both per capita and per dollar of GDP, than the Canadian average (Figure 5.2). In terms of intensity, Ontario and Quebec invest 55% more in R&D than Nova Scotia and British Columbia and nearly three times more than Saskatchewan and New Brunswick. While only around 80% of the Canadian average, R&D intensity in Nova Scotia and British Columbia is much higher than in provinces that rely more heavily on natural resources such as Alberta and Newfoundland and Labrador (Table 5.1).

48 Both are similar to the OECD average (2.4%).

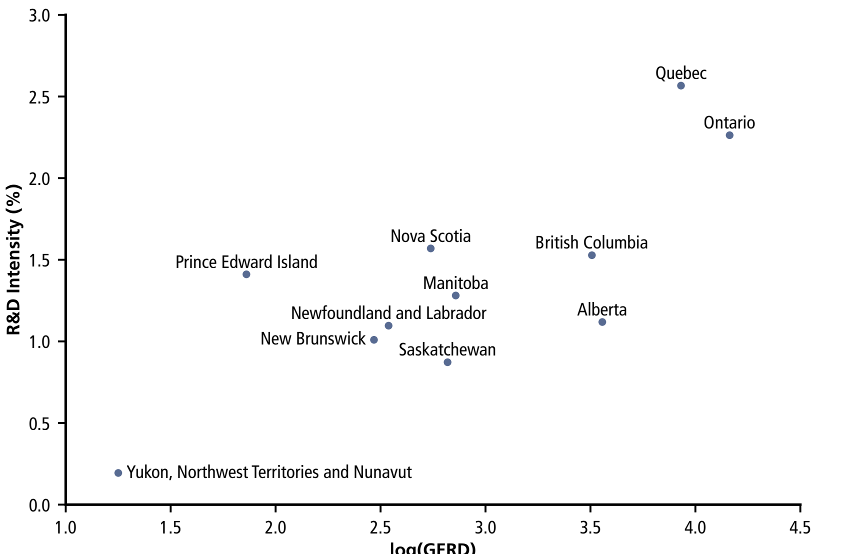


Data Source: OECD, 2016a; StatCan, 2016d, 2017h

Figure 5.1

International R&D Intensity and Spending, 2011–2015

The figure plots R&D intensity (GERD as a percentage of GDP) against R&D spending (log (GERD)) for 25 leading countries as well as Quebec and Ontario between 2011 and 2015. Both spending and intensity are calculated as the period average.



Data Source: StatCan, 2017h, 2017q

Figure 5.2

R&D Intensity and Spending by Canadian Provinces and Territories, 2011–2015

The figure plots R&D intensity (GERD as a percentage of GDP) against R&D spending (log(GERD)) for Canadian provinces and territories between 2011 and 2015. Both spending and intensity are calculated as the period average.

Virtually the entire decline in R&D spending from 2006 to 2015 occurred in Ontario and Quebec (Table 5.1). Richards *et al.* (2017) attribute much of this decline in Ontario to lower R&D spending in advanced manufacturing industries such as automotive, computer, and electronic manufacturing. The decline was driven by the loss of 30% of manufacturing firms and 40% of capital spending, and somewhat offset by spending gains among start-ups and other R&D service firms in life sciences, ICT, and creative industries. During this period, the share of this spending by foreign-controlled firms increased in Ontario (Richards *et al.*, 2017). Part of this decline in Quebec may be the result of the declining pharmaceutical manufacturing spending highlighted in Chapter 4.[49] While R&D spending increased in British Columbia and Alberta between 2006 and 2015, R&D intensity declined indicating that R&D is growing more slowly than GDP. By contrast, both spending and intensity increased in the Atlantic provinces (except New Brunswick). R&D is becoming slightly less concentrated across provinces (Table 5.1). These trends are driven by economic and other factors. Data do not permit a detailed analysis at the provincial level.

Table 5.1

Investment, Intensity, and Growth by Canadian Province and Territory, 2006–2015

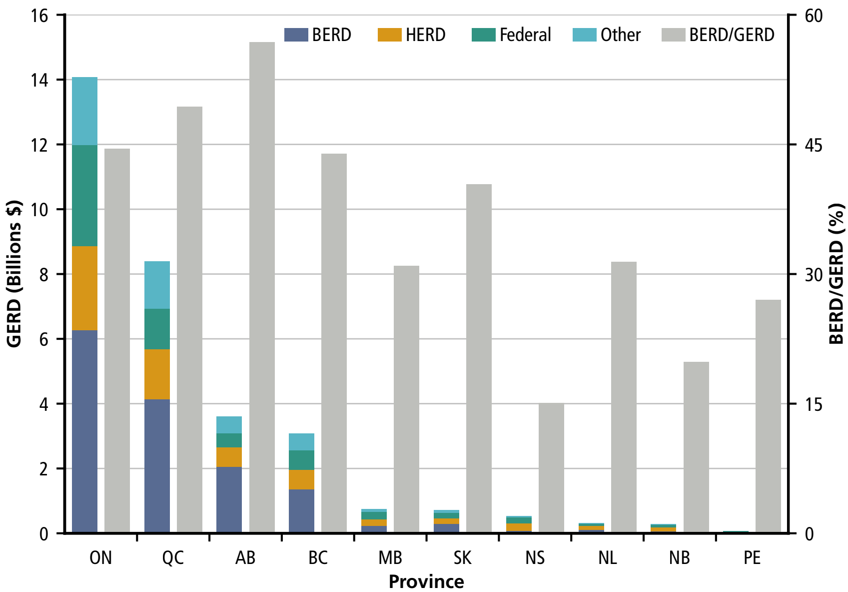
Province and Territory	2011–2015		2011–2015	2006–2015
	Magnitude (Billions $)	Share (%)	Intensity (%)	Growth (%)
Newfoundland and Labrador	0.35	1.1	1.10	2.17
Prince Edward Island	0.07	0.2	1.41	–0.16
Nova Scotia	0.55	1.7	1.57	0.53
New Brunswick	0.29	0.9	1.01	–0.56
Quebec	8.54	26.2	2.57	–0.81
Ontario	14.56	44.7	2.26	–1.16
Manitoba	0.72	2.2	1.28	2.19
Saskatchewan	0.66	2.0	0.87	3.13
Alberta	3.60	11.1	1.12	1.55
British Columbia	3.21	9.9	1.53	2.36
Yukon, Northwest Territories and Nunavut	0.02	0.1	0.19	2.05
Canada	32.58		1.87	–0.26

Data Source: StatCan, 2017h, 2017q

This table provides data on provincial total R&D spending (GERD) between 2006 and 2015: magnitude (average nominal GERD 2011–2015), intensity (average nominal GERD/average GDP 2011–2015), and growth (compound annual real growth 2006–2015). Green, yellow, and blue cells indicate the top three provinces by category for that indicator.

49 Recall from Chapter 4 that pharmaceutical spending on R&D has recovered since 2014.

Although the main sources of investment in R&D activities vary by province and territory, the Panel notes some facts about BERD in R&D across Canada.[50] In all but the Atlantic Provinces, BERD constitutes the largest single share of total R&D investment (Figure 5.3). However, only in Alberta is BERD greater than public investment in R&D (i.e., higher education R&D expenditures and government investment). In 2013, 57% of R&D investment in Alberta was performed by the business sector. This is similar to the OECD average (60%).



Data Source: StatCan, 2016d, 2017h

Figure 5.3

Source of R&D Investment and Share of Business Investment by Province, 2013

The figure plots GERD by performing sector (stacked bars), and BERD as a share of GERD (grey bars, right axis).

The rest of Canada relies more on the public sector than the private sector to invest in R&D. In Atlantic Canada, BERD is less than 30% of total R&D investments. The largest sources of investment are either higher education (New Brunswick, Newfoundland and Labrador, and Nova Scotia) or the federal government (Prince Edward Island). Total R&D investment in these provinces combined was less than foreign investment in Ontario alone in 2013. Similarly, investment by provincial governments and research and technology

50 Note that the remaining analysis is based on 2013 data.

organizations (RTOs) is also concentrated in Ontario and Quebec, with some notable investments in British Columbia and Alberta. Overall, provincial and territorial governments support around 6% of R&D across Canada (StatCan, 2017h).

The number of personnel engaged in R&D activities (including researchers, technicians, and support staff) as a percentage of the total population of a province or territory largely reflects the level of research investment. Averaged between 2005 and 2013, Quebec had the largest number of researchers per capita (1.76 per 1,000 residents), followed by Ontario (1.61), British Columbia (1.11), and Alberta (0.97). Furthermore, between 2005 and 2013, the R&D personnel-to-population ratio declined in every region except Saskatchewan, in which it increased by 24% (StatCan, 2013, 2016a).

5.2 PUBLICATIONS BY PROVINCE AND TERRITORY

Most Canadian publications are produced in Ontario, Quebec, British Columbia, and Alberta. Between 2009 and 2014, Ontario produced nearly half (46%) of Canada's publications. Together these four provinces accounted for 96% of all publication output in Canada. This is slightly more than their collective share of R&D investment (91%) and population (86%). These provinces also had among the fastest growth rates in the number of research publications during the period (Table 5.2).

The four provinces with the most publications also had the highest average and median impact. Between 2009 and 2014, British Columbia had the highest ARC score (1.69), followed by Ontario (1.54), Quebec (1.51), and Alberta (1.46). The remaining provinces and territories had ARC and MRC scores below the Canadian average. Yet, each province produced highly cited work in at least seven academic subfields, with pockets of unique research strengths in universities, labs, and firms across the country (see Tables A.6, A.7, A.8 in the appendix for additional bibliometric data on institutions). All provinces and territories increased both their publication output and impact between the 2003–2008 and 2009–2014 periods. Moreover, all provinces and territories had a higher impact than the world average or median between 2009 and 2014 (i.e., ARC and MRC > 1.0). During this period, growth in publication output was fastest in Newfoundland and Labrador, British Columbia, and Alberta.

Table 5.2

ARC, MRC, and Publications by Canadian Province and Territory, 2003–2014

Province or Territory	ARC			MRC		Publications (full count)			Publications per 1,000	
	2009–2014	2003–2008	Growth (%)	2009–2014	2003–2008	2009–2014	2003–2008	Growth (%)	2009–2014	2003–2008
British Columbia	1.69	1.59	6.3	1.75	1.73	74,162	55,030	34.8	16.0	12.7
Ontario	1.54	1.46	5.5	1.57	1.64	226,470	170,341	33.0	16.5	13.2
Quebec	1.51	1.39	8.6	1.60	1.57	110,433	84,228	31.1	13.4	10.9
Alberta	1.46	1.35	8.1	1.50	1.50	65,037	48,425	34.3	15.8	13.5
Nova Scotia	1.37	1.22	12.3	1.50	1.40	18,119	14,673	23.5	19.2	15.7
Saskatchewan	1.36	1.19	14.3	1.50	1.44	17,321	12,957	33.7	15.4	12.7
Yukon	1.36	1.12	21.4	1.31	1.50	226	172	31.4	6.1	5.2
Manitoba	1.34	1.22	9.8	1.40	1.38	16,659	12,475	33.5	13.0	10.4
Nunavut	1.32	0.90	46.7	1.67	1.19	154	125	23.2	4.3	3.9
Newfoundland & Labrador	1.26	1.22	3.3	1.40	1.33	6,814	4,825	41.2	12.9	9.4
Northwest Territories	1.25	1.07	16.8	1.50	1.29	274	224	22.3	6.2	5.2
New Brunswick	1.10	1.02	7.8	1.14	1.14	7,213	6,185	16.6	9.6	8.3
Prince Edward Island	1.08	1.06	1.9	1.25	1.26	1,338	1,179	13.5	9.2	8.5
Canada	1.43	1.36	5.1	1.50	1.50	496,696	377,779	31.5	14.0	11.4
World	1.00	1.00		1.00	1.00	12,935,138	9,006,984		1.8	1.3

Data Source: Calculated by the Panel and Science-Metrix using Scopus database (Elsevier)

The table presents ARC, MRC, and publications (total and per 1,000 residents). Provinces and territories are ordered by ARC score for 2009–2014. For the periods of 2003–2008 and 2009–2014, publications per capita data are based on population in 2008 and 2014, respectively.

5.2.1 Specialization

There is tremendous diversity in Canadian research, with all provinces and territories specializing in certain areas of R&D. Each produces at least twice as many publications as expected based on the world average in at least 15 academic subfields (SI > 2.0). Each has its own distinctive pattern of research output. Table 5.3 highlights some of the leading research subfields across Canada. Based on these subfield strengths (i.e., SI > 2.0 and/or ARC > 2.0), the final column suggests how closely they align with Canada's five fields of research strengths (see Chapter 3).

Provinces and territories with higher populations tend to specialize less than those with smaller populations (Figures E.1 and E.2 in the appendix). As a province or territory grows in population size, its research profile becomes more diverse and gradually resembles the world profile (Table 5.3). The four most populated provinces all have diverse research profiles, each with strengths in subfields related to at least two of the five fields of national research strength. Ontario, Quebec, British Columbia, and Alberta also produce publications in subfields related to the leading edge of global research, from astronomy to medicine to ICT. By contrast, smaller provinces in the Prairies and Atlantic Canada are highly specialized, often in fields related to natural resources such as agriculture, fisheries, and mining. Less populated provinces or territories, by virtue of their size, have more variable distributions of publications across fields than larger provinces (i.e., a smaller research base), and thus more specialization. This may also explain why seven of the nine subfields with both SI and ARC > 2.0 were in the Prairies and Atlantic Canada.

Table 5.3

Leading Research Subfields by Canadian Region, 2003–2014

Province	SI > 2.0		ARC > 2.0		SI > 2.0 ARC > 2.0	Research Strengths
	Total	Top 5	Total	Top 5		
British Columbia	29	• Forestry • Drama & Theatre • Fisheries • Geography • Ornithology	18	• General & Internal Medicine • General S&T • Mining & Metallurgy • Nuclear & Particle Physics • Astronomy & Astrophysics	• Software Engineering	• Visual & Performing Arts • Psychology & Cognitive Sciences • Clinical Medicine
Alberta	17	• Geology • Physiology • Sport, Leisure & Tourism • Sport Sciences • Medical Informatics	9	• General & Internal Medicine • Nuclear & Particle Physics • Anatomy & Morphology • Mining & Metallurgy • General Physics	• Forestry	• Clinical Medicine • Public Health & Health Services
Prairies	55	• Ornithology • Veterinary Sciences • Agronomy & Agriculture • Agricultural Economics & Policy • Physiology	18	• General & Internal Medicine • Nuclear & Particle Physics • Surgery • Allergy • Electrical Engineering	• Allergy • Criminology	• Clinical Medicine

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Province	SI > 2.0		ARC > 2.0		SI > 2.0 ARC > 2.0	Research Strengths
	Total	Top 5	Total	Top 5		
Ontario	20	• Drama & Theatre • Rehabilitation • Gender Studies • Criminology • Experimental Psychology	11	• General & Internal Medicine • Nuclear & Particle Physics • Gastro & Hepatology • Respiratory System • Dermatology		• Visual & Performing Arts • Psychology & Cognitive Sciences • Clinical Medicine • Public Health & Health Services • Philosophy & Theology
Quebec	15	• Forestry • Econometrics • Industrial Relations • Developmental Psychology • Experimental Psychology	10	• General & Internal Medicine • Anatomy • General Physics • Music • Nuclear and Particle Physics		• Visual & Performing Art • Psychology & Cognitive Sciences • Clinical Medicine • Philosophy & Theology
Atlantic Canada	127	• Veterinary • Fisheries • Oceanography • Horticulture • History	18	• General & Internal Medicine • Dermatology • Food Science • Design Practice & Management • Mechanical Engineering	• Dairy & Animal Science • Food Science • Anesthesiology • Mathematics • Genetics & Heredity	• Clinical Medicine

Data Source: Panel analysis based on data from Science-Metrix using Scopus database (Elsevier)

The table presents the number of fields by region in which SI and ARC are greater than 2.0. It also lists the top five fields by each score by region. The final column indicates the congruence between regional and national research strengths.

5.2.2 Collaboration

As noted in Chapter 3, between 2003 and 2014, Canada's share of publications with international co-authors was about 44%. In contrast, the share of Canadian publications with domestic co-authors (from two or more provinces or territories) was about 20%.[51] The interprovincial collaboration rate is greater than the international collaboration rate only in Prince Edward Island and the Territories. The Panel notes that, although most provinces and territories have similar international collaboration rates (between 33 and 48%), the rate of interprovincial collaboration varies widely (between 15 and 87%) (Table 5.4).

Table 5.4

Interprovincial and International Collaboration Rates by Province and Territory, 2003–2014

Province or Territory	Collaboration Rates	
	Interprovincial (%)	International (%)
British Columbia	23.0	48.2
Quebec	16.9	43.8
Ontario	14.8	43.4
Alberta	24.5	42.5
Saskatchewan	33.9	41.7
Nova Scotia	34.7	40.9
Prince Edward Island	46.7	40.6
Manitoba	33.5	39.7
Yukon	79.4	39.0
Newfoundland and Labrador	33.6	38.7
New Brunswick	35.7	38.0
Nunavut	85.7	34.5
Northwest Territories	86.9	32.5
Canada	9.9	43.7

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

The table presents rates of interprovincial and international collaboration by province and territory.

51 The interprovincial collaboration rates (IPC) are computed on whole counts rather than fractional counts. For example, a publication with authors from four provinces would count as one for Canada and one for each of the provinces. This means that the IPC for the whole of Canada would be 1 out of 874,475 (Canada's whole publication count over 2003–2014) and the IPC for Ontario (for example) would be 1 out of 396,811 (the whole count for Ontario). Therefore, the interprovincial collaboration rate would be lower for Canada than for Ontario.

British Columbia has the highest rate of international collaboration. Between 2003 and 2014, it produced 48% of its publications with an international collaborator, followed by Quebec, Ontario, and Alberta (Table 5.4). On the other end of the spectrum, the Territories and Atlantic Canada have the lowest rate of international collaboration, with an average international collaboration rate score of about 35% and 40%, respectively. As British Columbia, Quebec, Ontario, and Alberta produce a large number of highly cited publications (Table 5.2), these research ideas occupy a large share of the leading edge of global research.

Between 2003 and 2014, Ontario and Quebec had the lowest rates of interprovincial collaboration (15% and 17%, respectively), followed by British Columbia (23%) and Alberta (24%). In contrast, the Territories and Atlantic Canada exhibit high interprovincial collaboration rates, perhaps due to their small number of research institutions. In both regions, this situation leads to networks that extend over several neighbouring provinces.

Across all provinces and territories, the rates of international and interprovincial collaboration shown in Table 5.4 are strongly and negatively correlated. It may be that these two types of collaboration are substitutes: the more of one, the less of the other. It may also be that researchers (on average) only have enough time to collaborate either internationally or domestically, or must compete in the global marketplace of ideas, with only the best collaborating internationally. This finding may reflect provincial research strength, research reputation, and population size (i.e., larger populations produce proportionally more research than smaller populations). As *Canada's Fundamental Science Review* points out, low interprovincial research collaboration may have a negative impact on Canada's research competitiveness, serving to "make a small nation even smaller" (Advisory Panel for the Review of Federal Support for Fundamental Science, 2017). Nonetheless, a high rate of international collaboration is a strong signal of the competitiveness of that research. It suggests that Canadian ideas are faring well in the global pool of research.

5.3 PATENTS BY PROVINCE AND TERRITORY

Ontario, Quebec, British Columbia, and Alberta account for 95% of Canadian patents granted by the USPTO, with nearly 60% produced in Ontario between 2003 and 2014 (Table 5.5). These four provinces all have specialized and impactful patents as shown in Table 5.6. Between 2003 and 2014, patent growth more than doubled in Newfoundland and Labrador followed by Prince Edward Island, Ontario, and New Brunswick.

Table 5.5

Patent Output and Growth by Canadian Province and Territory, 2003–2014

Province or Territory	# of Patents (2009–2014)	Share (2009–2014) (%)	International Patent Flow (2009–2014)	Growth Rate (2003–2014)
Ontario	13,844	59.9	–0.24	1.86
Quebec	4,116	17.8	–0.16	0.84
British Columbia	2,231	9.7	–0.41	1.19
Alberta	1,852	8.0	–0.24	1.29
Manitoba	389	1.7	–0.07	1.43
Saskatchewan	292	1.3	–0.33	1.44
New Brunswick	155	0.7	–0.31	1.82
Nova Scotia	149	0.6	–0.16	1.21
Newfoundland and Labrador	49	0.2	–0.36	2.15
Prince Edward Island	16	0.1	0.08	1.87
Yukon	3	0.0	–0.10	0.26
Northwest Territories	2	0.0	–0.18	–

Data Source: Calculated by Science-Metrix using USPTO database

The table presents the number of patent (fractional), patent share, flow, and growth by province and territory. Patenting activity is heavily concentrated in Ontario.

Except for Quebec, all provinces and territories filed more patents in the 2009–2014 period than in the 2003–2008 period. The decline in Quebec patenting is likely related to a decline in R&D investment in ICT, but may reflect other factors. As shown in Figure 5.4, between 2003 and 2014, patents more than doubled in Ontario and decreased by almost 30% in Quebec. Much of this divergence is driven by telecommunications patents, which have grown rapidly in Ontario (BlackBerry) and declined in Quebec (Nortel).

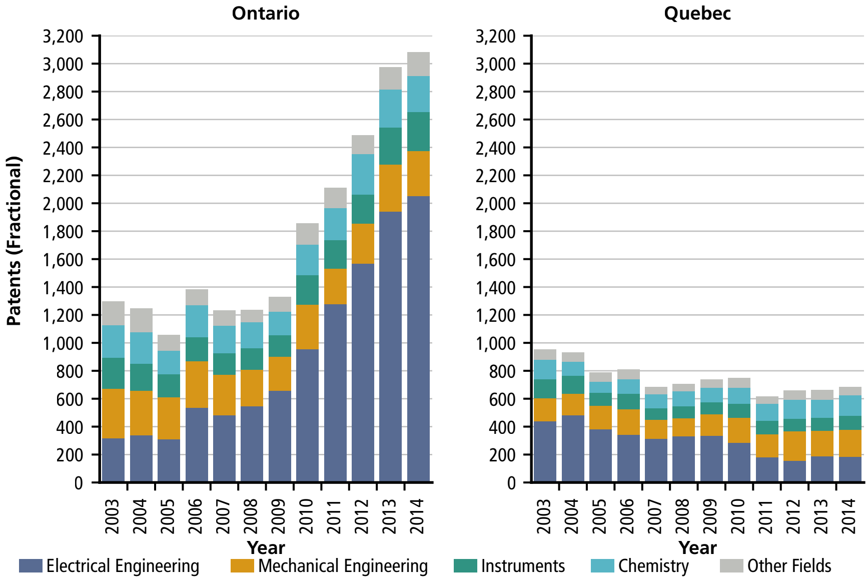
Table 5.6
Patents in Leading Canadian Provinces, 2009-2014

Province	ARC > 1.0 SI > 1.0	
British Columbia	• Pharmaceuticals • Electrical machinery, apparatus, energy • Medical technology • Measurement • Engines, pumps, turbines • Biotechnology	• Organic fine chemistry • Chemical engineering • Control • Mechanical elements • Environmental technology • Materials, metallurgy
Alberta	• Civil engineering • Measurement • Basic materials chemistry • Pharmaceuticals	• Handling • Biotechnology • Thermal processes and apparatus • Materials, metallurgy
Ontario	• Computer technology • Digital communication • Telecommunications • Basic communication processes	• Handling • Control • Thermal processes and apparatus
Quebec	• Engines, pumps, turbines • Digital communication • Telecommunications • Machine tools • Mechanical elements	• Organic fine chemistry • Other consumer goods • Materials, metallurgy • Environmental technology

Data Source: Calculated by Science-Metrix using USPTO database

The table presents technical fields in the leading provinces for which patents are both more specialized and impactful than the world average.

Except for Prince Edward Island, all Canadian provinces are patent exporters. This may reflect two factors. First, R&D investment by foreign-controlled firms in Canada has increased to more than 35% of total R&D investment (StatCan, 2017d) with Ontario leading the way (McKinsey & Company, 2016). It is likely that some of these patents will flow to investor countries. Second, Canadian inventors and companies are producing successful technologies that are in global demand. Technology exports may signal the strength of Canadian technology industries. Yet, they may also reflect a failure of Canadian industry to capitalize more fully on new technologies by growing ideas into large companies.



Data Source: Calculated by Science-Metrix using USPTO database

Figure 5.4

Patents in Ontario and Quebec, 2003–2014

The figure plots patents in Ontario and Quebec in five technical sectors between 2003 and 2014. The growth and decline in Electrical Engineering (dark blue bars) in Ontario and Quebec, respectively, is driven by patenting activity in the Telecommunications and Digital Communication subfield. This subfield was dominated by BlackBerry (Ontario) and Nortel (Quebec).

5.4 R&D CLUSTERS

Place matters. Beginning with the Industrial Revolution, people have been moving to cities at an exponential rate (Diamond, 1997; West, 2017). More than 80% of people in Canada live in cities today, up from only a few percent just 150 years ago (StatCan, 2011). Globally, more than half of the world's population is urbanized, with this proportion expected to rise to two-thirds by 2050 (UN, 2014).

There is strong evidence that R&D and economic activity *scale* in city size (Bettencourt *et al.*, 2007). As the population of a city doubles, "wages, wealth, and innovation increase by approximately 15% per capita" (West, 2017). This and other properties of cities have contributed to a divergence in the standard of living between urban and rural residents in Canada and throughout the world (Beckstead *et al.*, 2010; OECD, 2016a) (Box 5.1). Urbanization and scaling imply that if urban populations expand exponentially, cities will drive innovation and wealth creation at an *increasing rate* in the future (West, 2017).

Box 5.1
The Science of Cities

R&D activity is tightly linked to city size: the more people who live in a city, the more likely its inhabitants are to work in R&D, invent a patent, or build a technology company. Specifically, Bettencourt *et al.* (2007) find that indicators of R&D activity such as R&D employment, new patents, and R&D establishments tend to scale superlinearly. Rather than increase proportionally (one-for-one) with population, these indicators increase at a non-linear rate that is greater than one-for-one. They obey a power law scaling with an exponent of about 1.15 instead of 1.00. If a city were to double its population, the number of R&D jobs, patents, and companies, for example, would increase systematically by about 15% per capita. As city size increases, these indicators exhibit faster than exponential growth, and "explicitly show that cities are more than the linear sum of their individual components" (Bettencourt *et al.*, 2010). This is a powerful property of cities (West, 2017).

Cities provide two main benefits for firms: skilled people and dense networks (Glaeser, 2010; Behrens *et al.*, 2014). Dense populations allow people to specialize their skills and connect with others involved in research, technology, and business. Firms tend to locate in cities to benefit from skilled labour, knowledge spillovers, and specialized suppliers and infrastructure (CCA, 2013b). Firms in cities become more innovative because of their location, with cities acting like "giant matrices for recombining resources in order to generate innovations" (Veltz, 2004). Workers in large cities tend to be more productive than workers in smaller cities (Glaeser & Resseger, 2010), earning higher wages and having access to more technologies and services (Glaeser, 2011; Moretti, 2012). These benefits entice even more skilled people to move to cities, improving networks and advancing technology. Such cities are part of the "cognitive-cultural economy" (Scott, 2008) and often experience rapid population and economic growth (Davis & Dingel, 2017; Giannone, 2017).

Cities are simply the leading example of the more general process of clustering: the strong geographical concentration of research, technology, and economic activity. While all large cities contain clusters, many clusters are located in and around smaller cities and communities.[52] These clusters are often more closely linked to natural resources and long-standing economic and research strengths. Clustering, both in cities and regions, is associated with rapid innovation and economic growth (Delgado *et al.*, 2014).

52 Smaller cities and communities do not appear to follow scaling laws (West, 2017).

In general, the task of identifying clusters is difficult because of their complexity. A cluster is a "geographical proximate group of interconnected companies and associated institutions in a particular field, linked by commonalities and externalities" (Porter, 1998). They tend to emerge spontaneously, usually as a confluence of research, technology, and business activities, where the interactions of highly skilled workers and specialized firms produce knowledge spillovers (Krugman, 1991; Moretti, 2012). Identifying clusters is a challenge because it is difficult to establish statistical relationships between non-linear activities. Simple outcome measurements (e.g., patents, jobs, GDP) do a poor job of capturing the underlying non-linear reality.

Much of the work in cluster identification focuses on the United States (Porter *et al.*, 2001). Yet, as Wolfe and Gertler (2004) note, "national and local contexts are crucial in shaping distinctive evolutionary trajectories that do not necessarily conform to Porter's U.S.-based cluster norms." Based on this observation, Spencer *et al.* (2010) developed a methodology based on geographic patterns of co-location of employment in industries. Using the 2011 National Household Survey and this methodology, Spencer (2014) identified 230 clusters in Canada of 21 distinct types. The next two sub-sections are based on data from this paper.

5.4.1 Canadian Cities

While Canada's five largest cities account for about 2.5 times the population of the next 10 largest cities, they produce about 4.2 times as much innovation (as measured by patents and start-ups). This is because residents of Toronto, Montréal, Vancouver, Ottawa, and Calgary create patents and high-tech companies at nearly twice the rate of other leading cities. Figure 5.5 shows a strong positive relationship between population size and number of innovations across 15 Canadian cities.

As noted in Table 5.7, Canada's five largest cities are home to 44 unique clusters. This includes half of all of Canada's service clusters (business, ICT, finance, creative, and higher education) and numerous others in aerospace, automotive, ICT manufacturing, life sciences, and oil and gas. Both rates of innovation and types of clusters suggest that R&D activity is clustering in Toronto, Montréal, Vancouver, Ottawa, and Calgary. These cities are the predominant engines of innovation in Canada.

Table 5.7

R&D Spending and Innovation in Canada's 15 Largest Cities, 2011

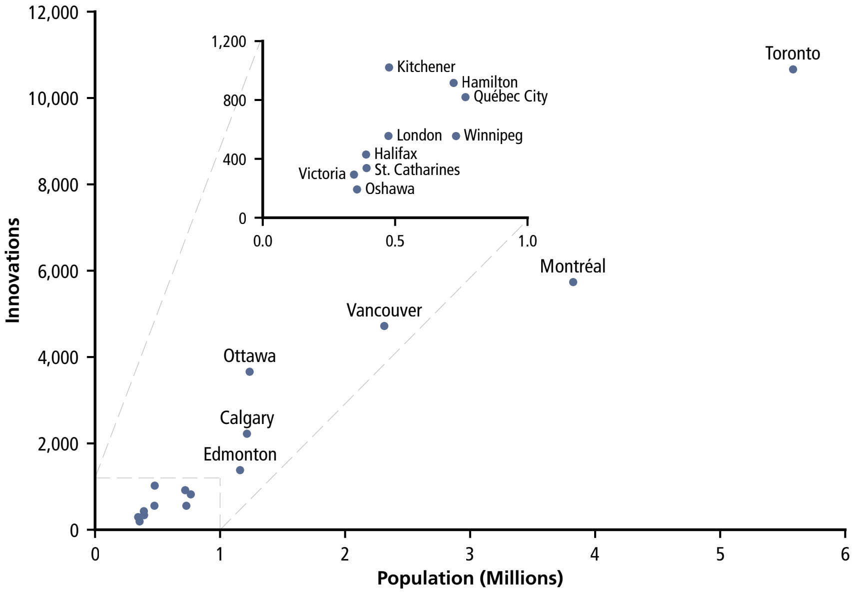
City	Population (Millions)	R&D Spending per Capita ($)	Patenting Rate	Start-Up Rate	Innovation Rate	Number of Innovation	Large Clusters (> 100k)	Clusters (< 100k)
Toronto	5.6	2,222	6	13.1	19.1	10,700	• Business Services • Finance • Logistics • ICT Services • Creative Services • Higher Education	• Food • Plastics • Automotive • ICT Manufacturing • Life Sciences • Textiles
Montréal	3.8	2,208	4.6	10.4	15.0	5,700	• Business Services • Finance • ICT Services • Logistics	• Creative Services • Food • Life Sciences • ICT Manufacturing • Aerospace • Textiles
Vancouver	2.3	1,510	9.2	11.2	20.4	4,700	• Business Services	• Finance • Construction • Logistics • ICT Services • Creative Services • Higher Education • Food • Maritime • Life Sciences

continued on next page

City	Population (Millions)	R&D Spending per Capita ($)	Patenting Rate	Start-Up Rate	Innovation Rate	Number of Innovation	Large Clusters (> 100k)	Clusters (< 100k)
Ottawa	1.2	4,286	16.8	12.8	29.6	3,700		• Business Services • ICT Services • Higher Education • ICT Manufacturing
Calgary	1.2	2,071	5.5	12.8	18.3	2,200	• Business Services	• Construction • Oil & Gas • Logistics • ICT Services • Mining • Steel • ICT Manufacturing
Top 5 Average	2.8	2,460	8.5	12.0	20.5	5,400		
Cities 6-15 Average	0.6	1,332	4.5	6.5	11.0	6,500		

Data Source: Spencer, 2014

Innovation rate (per 10,000 people) is calculated by adding patents (per 10,000 people) and start-ups (per 10,000 people) together. Number of innovations is calculated based on population. R&D spending is reported per capita. Large clusters have co-located employment of more than 100,000 people.



Data Source: Spencer (2014) and Panel calculations

Figure 5.5

Innovation and Population in Canada's 15 Largest Cities, 2011

The figure plots the number of innovations (patents and start-ups) against population for Canada's 15 largest cities. It displays a strongly positive relationship.

5.4.2 Canadian Regions

While increasingly clustering in cities, the remaining 80% of Canadian R&D remains relatively diverse. All provinces have at least one unique cluster, although about 90% of clusters are in Ontario (86), British Columbia (43), Quebec (42), and Alberta (30). The Prairies and Atlantic Canada account for fewer than 30 clusters (Spencer, 2014).

Clusters related to natural resources (74 of 230) exist in every province except Prince Edward Island. Between 2001 and 2011, the fastest growing clusters were in oil and gas. With the collapse in the price of oil, this is likely no longer the case (Spencer, 2014). As shown in Table 5.8, clusters tend to emerge around the location of natural resources, as is the case with forestry in British Columbia, oil and gas in Alberta, agriculture in Ontario, mining in Quebec, and maritime resources in Atlantic Canada. In some cases, the co-location of universities and a resource industry fosters a tight relationship between research and commercial success, such as that between the Université du Québec à Chicoutimi (UQAC) and Rio Tinto Alcan (Saguenay aluminium industry). This is demonstrated by high specialization and impact in geochemistry and geophysics (SI = 4.8, ARC = 2.1), applied physics (SI = 4.3, ARC = 2.0), and geology (SI = 17.2, ARC = 1.2). Several programs, such as the Industrial Research Chair (NSERC, 2017b) and Rio Tinto Alcan-CURAL Laboratory (Aluminium Research Centre, 2017), and a steady supply of UQAC engineering graduates, have helped build strong connections between academia and industry over time.

More than half of Canadian clusters are in manufacturing (118 of 230), with most in Ontario and Quebec (Spencer, 2014). The automotive, plastics, and steel industries have the most individual clusters. In Ontario alone, there are 16 unique clusters related to the automotive industry, 9 to steel, and 7 to plastics owing to the economic success of these industries in places such as Windsor, Hamilton, and Oshawa. Other advanced manufacturing industries such as aerospace, life sciences, and ICT tend to be more concentrated, often located near large research universities. As noted in Section 5.4.1, Canada's five largest cities account for half of all service clusters. The remainder are scattered across the country, generally located next to cities such as Victoria, Winnipeg, Waterloo, Fredericton, and St. John's. The following section looks at how the automotive cluster in Canada relies on R&D to maintain its global competitiveness.

Automotive R&D in Southern Ontario

The automotive industry is both the largest manufacturing industry and the largest export industry in Canada. In 2016, the industry contributed $18.8 billion to GDP, which represented about 11% of Canada's manufacturing GDP overall, and produced $59.4 billion of exports or about 15% of Canada's total (StatCan, 2018; OEC, n.d.). With nearly 90% of activity clustering in southern Ontario, this industry, from materials production to parts manufacturing to vehicle assembly, is essential to the provincial economy. Globally, the automotive industry is highly R&D intensive, ranking in the medium-high OECD industrial grouping, with an average intensity of more than 15% when measured as a share of gross value added (Galindo-Rueda & Verger, 2016). Yet, this is not the case in Canada. The domestic automotive industry ranks among the least R&D-intensive industries, investing at only about 12% of the OECD average and less than 6% of world-leading Japan. Specifically, in 2011, Canada ranked 26th out of 29 countries in R&D intensity in the motor vehicles, trailers, and semi-trailers industry (OECD, 2017a). In general, these seemingly inconsistent facts — low R&D intensity and high exports — are driven by the foreign control of Canadian industrial R&D.

Ontario is home to 11 assembly plants operated by five of the world's top automakers: General Motors, Ford, Chrysler, Honda, and Toyota. Overall, in 2014, these five original equipment manufacturers (OEMs) produced close to 2.4 million vehicles, approximately 2.7% of the world's supply. The first three, the so-called "big three," represent more than two-thirds of vehicle production. The Canadian automotive value chain also includes close to 400 establishments of primary automotive parts suppliers (producing primarily

Table 5.8

Summary of Clusters by Region, 2011

Province	Clusters	Resources	Manufac-turing	Services	Types (number of clusters)
Ontario	86	16	56	14	• Agriculture (9), forestry (1), maritime (1), mining (4), oil and gas (1) • Automotive (16), life sciences (3), food (6), ICT manufacturing (6), logistics (6), construction (1), plastics (7) steel (9), textiles (2) • Business services (3), creative and cultural (1), finance (3), higher education (5), ICT services (2)
British Columbia	43	20	15	8	• Agriculture (2), forestry (11), maritime (4), mining (2), oil and gas (1) • Construction (11), food (2), life sciences (1), logistics (1) • Business services (2), creative and cultural (1), finance (1), higher education (3), ICT services (1)
Quebec	42	12	26	4	• Agriculture (5), forestry (4), mining (3) • Aerospace (1), aluminum (3), automotive (3), life sciences (2), food (4), ICT manufacturing (2), logistics (1), plastics (6), steel (3), textiles (1) • Business services (1), creative and cultural (1), finance (1), ICT services (1)
Alberta	30	13	14	3	• Agriculture (1), mining (2), oil and gas (10) • Construction (9), food (1), ICT manufacturing (1), logistics (1), steel (2) • Business services (1), higher education (1), ICT services (1)
Atlantic Canada	18	7	3	8	• Forestry (2), maritime (3), mining (2) • Food (2), logistics (1) • Business services (3), higher education (3), ICT services (2)
Prairies	11	6	4	1	• Agriculture (2), mining (3), oil and gas (1) • Aerospace (1), life sciences (1), construction (1), textiles (1) • Higher education (1)
Total	230	74	118	38	

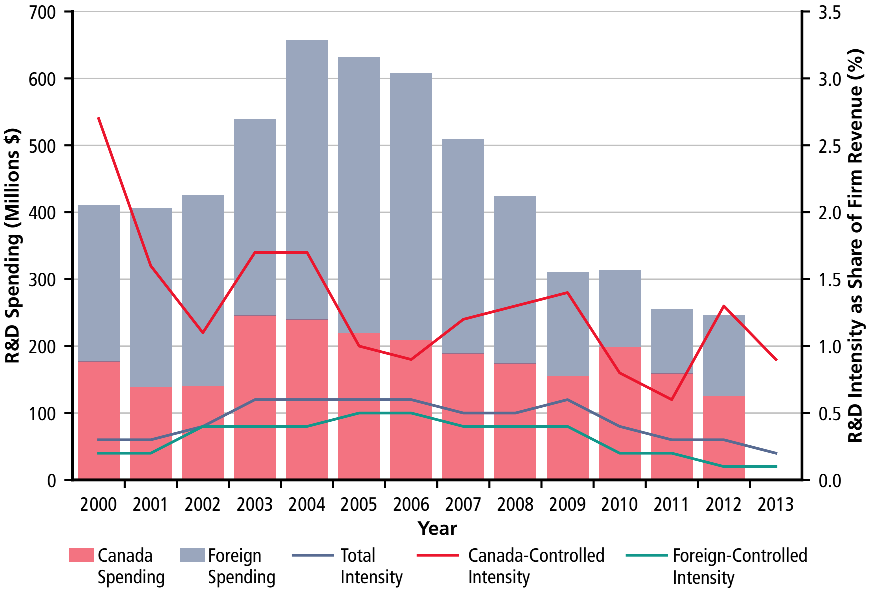
Data source: Spencer, 2014

This table shows the number of clusters by province, sector, and industry.

for the OEMs) and many establishments of diversified parts suppliers (for whom OEM supply is not the primary line of business) (Sweeney & Mordue, 2017). Parts suppliers include many SMEs at the lower end of the value chain. The sector is highly concentrated in southern Ontario, which is home to over 300 auto parts manufacturers including ABC Group, Woodbridge Group, Linamar, and Magna International (North America's largest manufacturer) (Sweeney & Mordue, 2017).

In the wake of the 2008–2009 financial crisis, the industry started to undergo a fundamental restructuring, during which three OEM plants and several parts supplier plants were closed, leading to a temporary decline in employment and vehicle output (Sweeney & Mordue, 2017). The recovery was not only marked by economic challenges and increased competition, but also by a new and complex set of innovation challenges arising from a shift of innovation from a single firm, usually the OEM, to a broader network of firms along the supply chain. The shift was driven by the increased reliance of automotive R&D on "combinatorial knowledge," which combines formerly discrete knowledge bases, rather than "cumulative knowledge," which builds on existing knowledge stocks (Goracinova *et al.*, 2017). The creation of combinatorial knowledge requires more integrated networks and partnerships among the various actors along the supply chain, including OEMs, parts suppliers, universities, research centres, and start-up companies. Such innovation networks can be supported by adjusting automotive policies to reflect the need for "new forms of collaborative or networked governance to promote more effective technology development and diffusion across the supply chain" (Goracinova *et al.*, 2017).

Overall, R&D in the Canadian automotive industry is declining. Motor vehicle and parts manufacturing R&D reached $657 million in 2004, but decreased to an anticipated $211 million in 2017 an amount similar to spending in the late 1990s. Between 2000 and 2012, foreign-controlled investment (about half from the United States) declined relative to Canada's investment: Canadian-controlled R&D declined by 2.9% while foreign-controlled R&D declined by 5.3%. In 2001, almost two thirds of automotive R&D in Canada was foreign-controlled. By 2012, it was less than half (Figure 5.6). Similarly, although the intensity of Canadian-controlled R&D fell from 2.7% to 1.3% between 2000 and 2012, it remained much higher than both the intensity of foreign-controlled R&D (0.3%) and the overall intensity of R&D in the Canadian automotive industry (0.4% when measured as share of revenue) (Figure 5.6). Given spending trends, this implies that foreign-controlled automotive companies generate significantly more revenue than Canadian-controlled companies. The poor performance of Canadian automotive R&D is mostly driven by foreign-controlled companies, which have decrease spending since 2004 and invest at a low intensity.



Data Source: StatCan, 2017a, 2017d

Figure 5.6

Automotive R&D Spending and Intensity in Canada, 2000–2013

This figure plots R&D spending and intensity in the Canadian automotive industry by country of control. Data on spending country of control is only available up to 2012.

5.5 CONCLUSION

Ontario leads Canada in R&D investment and performance. The province accounts for almost half of R&D investment and personnel, research publications and collaborations, and patents. R&D activity in Ontario produces high-quality publications in each of Canada's five R&D strengths, reflecting both the quantity and quality of universities in the province. Quebec lags Ontario in total investment, publications, and patents, but performs as well (citations) or better (R&D intensity) by some measures. Much like Ontario, Quebec researchers produce impactful publications across most of Canada's five R&D strengths.

Although it invests an amount similar to that of Alberta, British Columbia does so at a significantly higher intensity. British Columbia also produces more highly cited publications and patents, and is involved in more international research collaborations. R&D in British Columbia and Alberta clusters around Vancouver and Calgary in areas such as physics and ICT and in clinical medicine and energy, respectively. Smaller but vibrant R&D communities exist in the Prairies and Atlantic Canada (and, to a lesser extent, in the Territories) in natural resource industries.

Globally, as urban populations expand exponentially, cities are likely to drive innovation and wealth creation at an increasing rate in the future. In Canada, R&D activity clusters around five large cities: Toronto, Montréal, Vancouver, Ottawa, and Calgary. These five cities create patents and high-tech companies at nearly twice the rate of other Canadian cities. They also account for half of clusters in the services sector, and many in advanced manufacturing.

Many clusters relate to natural resources and long-standing areas of economic and research strength. Natural resource clusters have emerged around the location of resources, such as forestry in British Columbia, oil and gas in Alberta, agriculture in Ontario, mining in Quebec, and maritime resources in Atlantic Canada. The automotive, plastics, and steel industries have the most individual clusters as a result of their economic success in Windsor, Hamilton, and Oshawa. Advanced manufacturing industries tend to be more concentrated, often located near specialized research universities. Strong connections between academia and industry are often associated with these clusters.

R&D activity is distributed across the country, varying both between and within regions. It is critical to avoid drawing the wrong conclusion from this fact. This distribution does not imply the existence of a problem that needs to be remedied. Rather, it signals the benefits of diverse innovation systems, with differentiation driven by the needs of and resources available in each province.

6

Barriers in Translating R&D into Innovation and Wealth Creation

- R&D, Innovation, and Wealth Creation: Understanding the Links
- Barriers to Translating R&D into Technological Innovation
- Barriers to Translating Technological Innovation into Wealth Creation
- Conclusion

6 Barriers in Translating R&D into Innovation and Wealth Creation

Key Findings

Few barriers impede the translation of R&D into technological innovation in Canada. Significant barriers, however, prevent the translation of technological innovation into wealth creation.

- Surveys show that Canadian firms have high rates of innovation, especially among SMEs.
- Academia-business R&D linkages appear robust relative to other countries given the extent of cross-sectoral research funding and increasing numbers of research partnerships.
- While Canadian universities have lower rates of technology licensing than U.S. institutions, internationally comparable data on rates of research commercialization are sparse and often inconclusive.

Canada is highly competitive internationally in providing a supportive environment for entrepreneurs and technology start-ups.

- Macroeconomic and social environments are stable and attractive, R&D tax support is comparatively generous for small firms (though now less competitive for larger ones), barriers to business creation are low, and entrepreneurial ambition is widespread. Many Canadian cities are now home to thriving communities of tech start-ups.
- Venture capital availability has improved greatly in recent years. Canada now ranks third in the world on venture capital investments as a share of GDP.

Canada's industrial structure and economic integration into North American supply chains contribute to comparatively lower rates of industrial R&D investment.

- R&D is less central to Canadian business strategy. Rather the focus is on intrinsically less technology-focused industries such as mining and wholesale trade.
- In several high-tech industries, relatively weak industrial R&D is driven by low U.S. investment in Canadian operations in industries such as automotive and pharmaceutical manufacturing.

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Canada grows only a few Canadian-owned R&D-intensive firms and lacks critical skills in industry for the commercial exploitation of R&D advances.

- Successful Canadian technology start-ups often struggle to grow to scale domestically and internationally.
- Many entrepreneurs plan to sell their firms rather than grow them in the small Canadian market, limiting subsequent economic benefits.
- Recent survey evidence identifies lack of managerial skills as an impediment for scaling start-ups.

Subpar business investment in R&D and its implications for innovation are a perennial source of concern in Canada. Business R&D spending in Canada has been comparatively low for decades and has declined further in recent years. A Senate committee on science policy in 1970 noted that successive Canadian governments have been trying — and failing — to promote technological innovation in industry since 1916 (Senate Special Committee on Science Policy, 1970). The declines and concerns continue. The entrenched nature of Canada's lower levels of business spending on R&D has recently led to speculation that it reflects a deep, structural feature of Canada's economic integration into the North American economy (CCA, 2013c; Nicholson, 2016). Moreover, Canada's productivity growth rate has persistently lagged behind that of the United States since the mid-1980s, leading to a widening productivity gap. This has been attributed to lower MFP growth, which is typically interpreted as an indicator of poor innovation performance (StatCan, 2007; Baldwin & Gu, 2009; Bibbee, 2012).

Low levels of Canadian business R&D, however, are perplexing for several reasons. First, as documented in this and many previous reports, Canada's scientific capacity and research output are of high quality and competitive with other leading countries (CCA, 2012a, 2013c, 2016). Second, framework conditions in Canada are highly favourable for business risk-taking and innovation. Canada benefits from a stable macroeconomic environment, a relatively open economy, a highly skilled and educated population, low corporate tax rates, low barriers to firm entry, and flexible labour markets (Bibbee, 2012). Researchers and policy-makers have consequently struggled to identify the causes of Canada's subpar performance, often suspecting that barriers are preventing Canada from fully capitalizing on its research strengths, and attaining higher levels of innovation.

In this chapter, the Panel surveys evidence on barriers to the translation of Canada's research strengths into innovation and wealth creation, responding to the final sub-question in its charge. Section 6.1 reviews the relationship between R&D and innovation and the points in this process where barriers can arise. These barriers differ depending on whether they relate to challenges in translating R&D into technological innovation (reviewed in Section 6.2), or to translating technological innovation into wealth creation (reviewed in Section 6.3). Section 6.4 synthesizes the evidence and states the Panel's main conclusions.

6.1 R&D, INNOVATION, AND WEALTH CREATION: UNDERSTANDING THE LINKS

R&D and innovation are distinct, though related, activities. Table 6.1 provides a summary and comparison of the two terms. Innovation — the introduction of new products, processes, organizational methods, or marketing methods — is common among Canadian firms, nearly two-thirds of which report introducing some form of innovation over a three-year period (StatCan, 2014a). Investing in R&D, by comparison, is rare. Only around 2% of Canadian firms perform R&D (StatCan, 2015). R&D, however, is a critical input to technological innovation (i.e., the development of new technologies forming the basis of new products or processes).[53]

Table 6.1

Comparing R&D and Innovation

R&D	Innovation
• Consists of all activities undertaken to generate new knowledge or spur technological advances. • Encompasses the entire range of research disciplines, from the natural and applied sciences to the humanities and arts. • Also spans the full range of research activities from pure, basic research through to applied R&D. • Undertaken in all sectors (academia, government, industry, and not-for-profit), though basic research tends to be concentrated in academia while experimental development is more actively pursued in the private sector. • Can be undertaken in-house or contracted out to other firms or research organizations (either in Canada or elsewhere). • Benefits society in many ways — one of which is an increased potential for technological innovation.	• Consists of the implementation of new or improved products and processes, or new or improved marketing or organizational methods. • Sometimes *related* to R&D and technological advances (i.e., with development or adoption of new technologies arising from R&D activity). • Sometimes *unrelated* to R&D (e.g., with change in marketing strategies or business organization). • Typically associated with firms, but can occur in not-for-profits and the public sector. • Can be developed in-house or adopted based on products or processes developed elsewhere. • Leads to economic benefits by increasing productivity at the firm level and throughout the economy as a whole. • Central driver of national competitiveness and economic growth over the long term.

53 R&D is sometimes classified as one type of *innovation activity*, with others including capital investment and training. Non-R&D innovation inputs tend to be poorly measured, which is one reason the two concepts are routinely conflated. A current review of the challenges associated with measuring innovation and related concepts can be found in NASEM (2017).

Innovations can be *radical*, such as an entirely novel, disruptive technological advance, or *incremental*, the gradual improvement of existing products or processes. The discussion of innovation in this chapter focuses primarily on innovation in firms based on available data, but the concept need not be restricted to the private sector (Box 6.1). Innovation is also influenced by a large number of external drivers unrelated to R&D, such as the macroeconomic context; tax and regulatory regimes; the availability of financing, skills, and talent across different levels of development; and the existence of firms in a supportive web or relationship of research networks and partnerships (CCA, 2013b). National innovation performance is a function of these elements; deficits in any one area may impinge on the extent of innovative activity.

Box 6.1
Defining and Measuring Social Innovation

Innovation is not solely the prerogative of the private sector. Not-for-profit and public-sector organizations innovate as well, potentially increasing their effectiveness or efficiency in the process. Interest in the concept of *social innovation* (and related terms such as *social entrepreneurship* and *social enterprise*) has been increasing throughout the 21st century, both globally and in Canada (Phills *et al.*, 2008; Goldenberg *et al.*, 2009; PRI, 2010; Nicholls & Murdock, 2012; ESDC, 2017). The inaugural issue of the *Stanford Social Innovation Review* defined *social innovation* as "the process of inventing, securing support for, and implementing novel solutions to social needs and problems" (Phills *et al.*, 2008). Social innovation may entail the implementation of new technologies by governments and non-governmental organizations working to provide public services or address social issues. It may also involve the creation of organizational models that challenge traditional boundaries between the public, private, and not-for-profit sectors (Phills *et al.*, 2008). Micro-finance initiatives, for example, involving the extension of small loans to citizens in low-income countries, can challenge the distinction between for-profit and charitable organizations. Standard measurements have focused on assessing innovation activities in firms, and there is a lack of systematic data collection in other arenas. However, organizations such as the OECD have undertaken initial research on public-sector innovation (OECD, 2017b), and discussions are underway about how traditional definitions and measurement tools could be adapted (NASEM, 2017). Such changes may eventually allow more comprehensive assessments of social or public-sector innovation, complementing those available for innovation in firms.

Much commentary on the role of R&D and innovation in supporting economic growth creates the impression that the link between the two is simple and direct. Early advocates for science in the 20th century such as Vannevar Bush subscribed to a linear model connecting research and innovation, with advances in R&D leading directly to new technologies, which then increase productivity and create economic prosperity (Bush, 1945; Stokes, 1997). Most researchers have since come to understand that the linkages are more complex. R&D and innovation are recognized as multifaceted social phenomena, replete with feedback loops running in multiple directions (CCA, 2013b). Recent models of innovation systems also highlight the dependence of R&D and innovation on a variety of environmental factors, and on the complex interactions between innovation actors (Adner, 2006; Jackson, 2011; CCA, 2013b). Impediments to the translation of R&D into innovation and aggregate economic and social benefits can therefore occur at multiple points in the system. Survey evidence from Canadian firms (Box 6.2) illustrates the range of obstacles that can arise, but firm perceptions alone may not fully reflect structural or systematic causes.

Box 6.2
Innovation Obstacles: Survey Evidence from Canadian Firms

Survey evidence suggests that Canadian firms encounter a range of obstacles in their pursuit of innovation. Figure 6.1 presents data from Statistics Canada showing firm perceptions drawn from innovation survey data. Two features of these data stand out. First, the evidence shows a reduction in the number of firms reporting most types of innovation obstacles between 2009 and 2012. This may reflect increased business optimism in the face of improving economic conditions following recovery from the 2008–2009 global financial crisis; however, it may also indicate that conditions for innovation in Canada are improving. Second, evidence suggests that the most common obstacles to innovation for firms are, in order of importance: uncertainty and risk, lack of skills, internal financing, market size, regulatory issues, and external financing. Fewer than 5% of firms reported facing challenges related to government competition policy or IP protection in either year.

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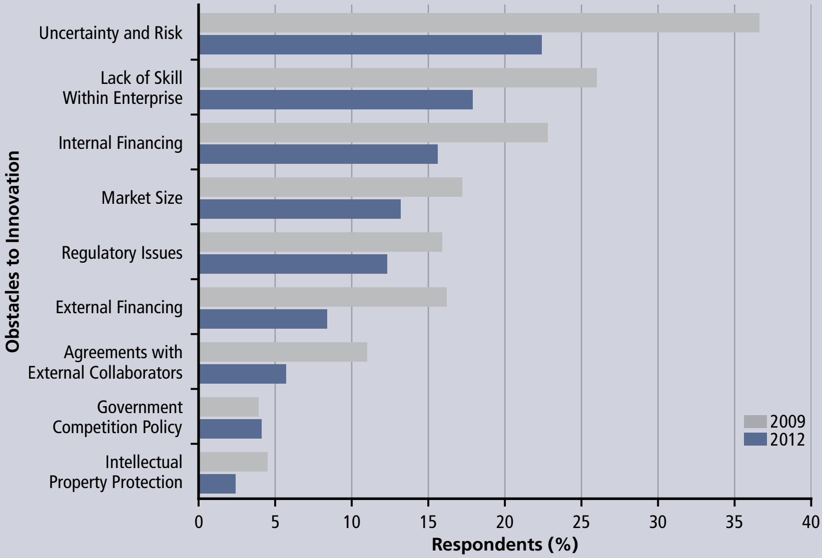


Data Source: StatCan, 2014b

Figure 6.1

Obstacles to Innovation Reported by Canadian Firms, 2009 and 2012

The innovation environment for Canadian firms appeared to improve between 2009 and 2012. Firms reported declines in nearly all common obstacles. This is likely a reflection of the stabilization of economic conditions following the 2008–2009 financial crisis, but may also reflect an improvement in skill availability, financing, regulatory issues, and collaborative agreements. Note that, between the two years covered, there was a small decline in the overall percentage of reporting firms that introduced an innovation; fewer firms pursuing innovation may have also contributed to fewer firms reporting encountering innovation obstacles.

Figure 6.2 represents the relationships between R&D, innovation, and wealth creation. The translation of R&D into innovation is distinct from the translation of innovation into wealth creation. The former involves the creation of new products and processes (and, potentially, new marketing or organizational methods), building on technological advances from R&D activities. The latter involves commercializing those technological innovations in a way that yields widely dispersed economic and social benefits. To illustrate the distinction, consider the creation of a start-up to commercialize a new technology based on cutting-edge research. This is an example of moving from R&D to technological innovation. Growing that start-up to the point where it generates economic or social benefits for the surrounding community or region is an example of translating an innovation into wealth creation. Successful innovations elicit a positive feedback cycle, generating commercial and social returns that can be reinvested into R&D infrastructure or personnel and innovation activities to catalyze future innovations.

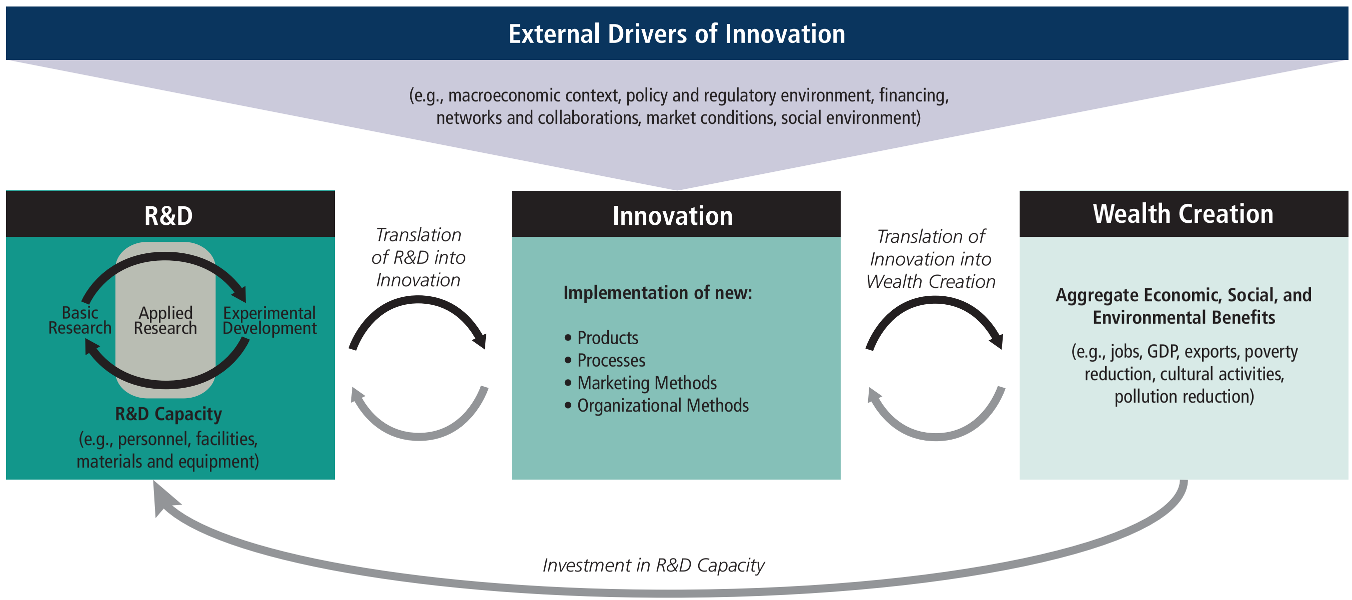


Figure 6.2

Understanding the Links Between R&D, Innovation, and Wealth Creation

The translation of R&D into innovation and wealth creation is complex, occurring through distinct stages. Advances in basic research and experimental development are mutually supportive (linked, in many cases, through applied research). R&D feeds into innovation by supporting the creation of new products, processes, and marketing or organizational methods. This chapter focuses primarily on product and process innovation as those types of innovation are more closely linked to R&D and technology development. Innovations are also fed by external drivers such as macroeconomic context, policy, regulatory or social environments. Innovations lead to economic benefits through productivity increases, job creation, GDP growth, etc. Innovations may also provide other social benefits, such as reducing environmental impacts or improving the efficiency or effectiveness of public services.

R&D and resulting innovations do not necessarily co-occur within the same firm. Much innovation arises from purchased R&D, whether in the form of R&D contracts with Canadian and foreign research institutions, or through the importation and adoption of products and processes developed in other countries (Engardio *et al.*, 2005). Canadian firms may also benefit from R&D undertaken by foreign firms, both directly through formal channels such as contracts and licensing agreements, and indirectly through the informal transfer of knowledge in non-codified ways. In addition, one of the reasons for undertaking business R&D is to enable the adoption and adaptation of externally sourced innovation. As a result, Canadian innovations may have their origins in R&D undertaken elsewhere. Similarly, Canadian R&D efforts may support innovations developed abroad when they do not lead to new innovative activity in Canadian firms. Coupled with the integration of Canadian firms into North American supply chains (Section 6.3.2), this may contribute to the apparent disjunction in R&D expenditures and rates of reported innovation in Canadian firms.

6.2 BARRIERS TO TRANSLATING R&D INTO TECHNOLOGICAL INNOVATION

Research commercialization (i.e., the translation of research into a marketable technology, product, or service) is the first step in transforming research to innovation and wealth creation, and Canada's record of research commercialization has sometimes been criticized (Expert Panel on Commercialization, 2006; CCA, 2009; Galushko & Sagynbekov, 2014). Subpar commercialization may be the result of various barriers preventing the efficient translation of research into technological innovations that firms can commercialize, such as a disjuncture between academic and industry cultures and reward systems, poor academia-business linkages or low business receptor capacity for research, and challenges arising from IP policies and management.

6.2.1 Research Commercialization Indicators and Measurement

Common indicators used to track research commercialization activity include invention disclosures; patents granted and patent applications; licensing deals and income; spin-off companies; technology transfer office characteristics (including funding, revenues, employment); and industry-funded R&D at universities and public research institutions. Measurement challenges, however, limit the evidence and make international comparisons problematic. Unlike R&D and innovation, research commercialization indicators have not been standardized by the OECD or national statistical agencies (Arundel & Bordoy, 2008). Systematic data collection guidelines (such as those provided by the Frascati and Oslo manuals) are lacking. Data are often reported and collected using one-off national surveys or annual surveys of member organizations, such as the survey from the Association of University Technology Managers (AUTM) and the Association of European Science and Technology Transfer Professionals (ASTP). Differences in survey methodology and the sample of institutions may also affect results and hamper international comparability (Arundel & Bordoy, 2008). Data from these sources must also be normalized by research funding or some other factor to yield insightful comparisons across institutions (Arundel & Bordoy, 2008).

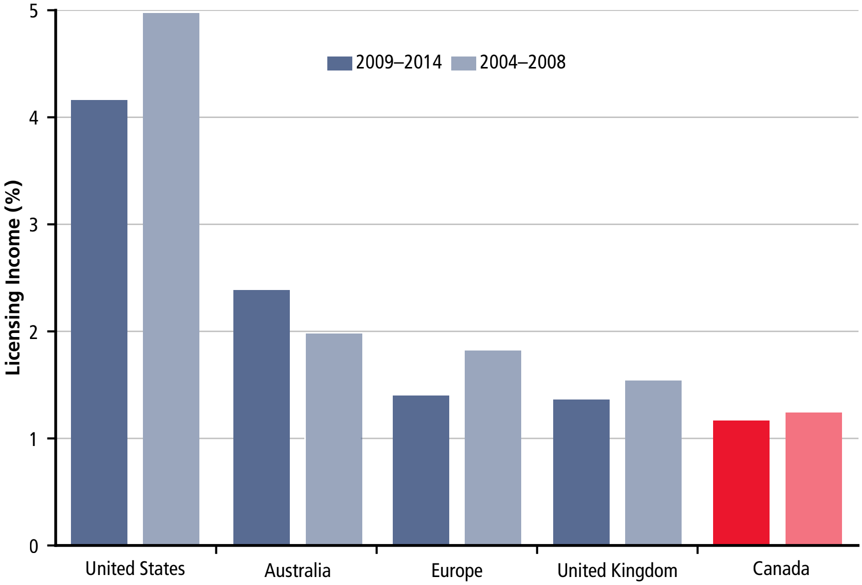
6.2.2 University Research Commercialization Performance

Canadian data on research commercialization can be drawn from the annual AUTM survey, in which a subset of universities and technology transfer offices (TTOs) participate. For the 2004–2009 period, data were also collected through Statistics Canada's *Survey of Intellectual Property Management*; that survey, however, was discontinued after 2009, leaving a significant gap in research commercialization data.[54] AUTM survey data are based on surveys received from a sample of Canadian higher education institutions. These data show that commercialization activities have increased steadily by many measures in Canada since the early to mid-1990s, alongside rising research expenditures. Invention disclosures increased from 250 in 1991 to over 1,800 in 2015. Similarly, licences and options executed have grown to over 700 in 2015, and the number of start-ups based on research undertaken at Canadian universities has also increased, from 29 new companies in 1994 to 90 in 2015. Licensing income reported by TTOs has been variable over the years and stood at $62 million dollars in 2015, down by 29% since 2014, but up by a factor of 10 since 1991 (AUTM, 2015b).

The fact that few Canadian TTOs have been able to generate significant income streams has been seen as evidence of their relatively poor performance (CCA, 2009), though for most countries, a small number of research performing institutions account for the bulk of licensing revenues (OECD, 2016f). In Canada, the University of Toronto is by far the largest recipient of licensing income, and only three institutions (University of Toronto, University of Saskatchewan, and University of British Columbia) received more than $5 million in licensing revenue in 2014 (AUTM, 2015a). Moreover, the majority of academic licensing income arises from a small number of patents (Cervantes, n.d.). In the University of Saskatchewan's case, for example, the largest share of licensing revenue comes from a patent for circovirus vaccine for swine (Yates, 2012).

54 With budget cuts implemented in 2009, Statistics Canada, taking a systems approach, made the decision to cut linkage measurement and retain activity (R&D and innovation) measurements. Provincial surveys were cut at this time as well as surveys of IP practice in the federal government. However, to understand both systemic and market failures associated with innovation, measuring these linkages is essential.

Given data limitations, it is difficult to compare Canada's track record with that of other countries. When it comes to licensing income as a percentage of research expenditures, Canadian academic institutions have not done as well as many other countries. OECD data show that Canada's licensing income from public research institutions was on average 1.2% of research expenditures between 2009 and 2014 (Figure 6.3), compared with 4.2% for the United States, 1.4% for Europe, and 2.4% for Australia.



Data Source: OECD, 2016f

Figure 6.3

Licensing Income from Public Research as a Share of Research Expenditures, 2004–2014

Canada's licensing income from public research institutions relative to research expenditures is low relative to the United States and Australia, though more comparable to the levels in Europe and the United Kingdom. Data for Europe are for only for 2004–2011 and the 2009–2014 average is based on the latest data available.

In the Panel's experience, low licensing income poses a sustainability challenge to TTOs, which may then lack the funding necessary to support their operations. This challenge is made more acute by the diversity of research and technologies that TTOs may encounter. Without the resources and expertise needed to assess potential applications across a wide range of scientific and technical domains, TTO staff may struggle to correctly assess the commercial potential of research brought to their attention, thereby limiting their effectiveness and impact.[55]

55 These challenges can be exacerbated or ameliorated by the culture of the institution and factors such as whether it is run by research administrators or entrepreneurs, the influence of the primary investigators, and how much commercial pull is taken into account when pursuing spin-off creation and licensing.

Pushing TTOs to be financially self-supporting through licensing revenue, however, may be inappropriate to the extent that TTOs provide a public service by addressing market failures in commercializing early-stage research.

The Science, Technology and Innovation Council (STIC) *State of the Nation Report 2014* found that Canadian higher education institutions lag behind their U.S. counterparts when it comes to licences and licensing revenue (STIC, 2015). According to this report, Canadian universities created approximately 16 licences per institution in 2012 compared with 35 in the United States. Canadian institutions received, on average, approximately $2.2 million from licensing income whereas U.S. institutions averaged US$13.5 million. These comparisons suggest that Canadian performance on technology transfer continues to trail U.S. performance.[56] On other research commercialization measures, internationally comparable evidence is limited. Arundel and Bordoy (2008) provided international comparisons across a range of commercialization measures after standardizing the indicators used. According to their analysis, Canada led the United States, United Kingdom, Europe, and Australia on patent applications per research expenditure, and had scores similar to these countries on many other measures, including invention disclosures, patents granted, licences executed, and start-ups. This analysis was based on data from 2004, however, and has not been repeated.

6.2.3 Academia-Business Cultural Divide

University researchers operate in a different professional context than their peers in the private sector. In particular, their professional incentives and goals are often driven by the pursuit of recognition for their research achievements, as demonstrated through scholarly publications. That recognition takes the form of professional advancement (e.g., tenure), peer esteem, and research grants, prizes, and awards (Stephan, 2012). In this context, there may be limited incentives for university-based researchers to invest their limited time in activities aimed at commercializing their findings (or translating them into social goods in other ways), especially when such activities are not aligned with either their professional goals or personal motivations. This distinction between the incentive structures faced by university-based researchers and those

56 Scale effects might partially explain these differences, as U.S. institutions also have higher levels of research expenditure, on average, than Canadian ones. However, even when U.S. institutions with annual research expenditures above those of the University of British Columbia (Canada's top-spending institution in the AUTM data) are removed from consideration, a substantial gap remains between Canadian and U.S. institutions on licensing income as a share of research expenditures. Between 2011 and 2015, Canadian institutions averaged 1.2% compared with 4.9% among similarly sized U.S. institutions.

operating in the private sector has sometimes been identified as a source of friction in the research commercialization process in Canada and elsewhere (CCA, 2009, 2013b).

In this respect, Canada follows global norms and practices in academia and industry. While university support for research commercialization varies across institutions, and promotion and tenure policies may differ in the degree to which they recognize commercial achievements, there is little evidence that Canadian institutions differ systematically in this respect from their counterparts in the United States or other countries.[57] Conflicting academic and industry incentive structures contribute to research commercialization challenges in many countries. However, some evidence considered by this Panel points to the possibility that this cultural gap may be more significant in Canada than elsewhere. For example, the World Economic Forum currently ranks Canada 24th on the extent to which business and universities collaborate on R&D based on a survey of business and government leaders, indicating a widespread perception that Canadian academics and universities continue to be less prone to collaborating with industry than researchers in many countries (WEF, 2017). This may be particularly true in the United States and Europe, where there is sometimes greater prestige associated with collaborating with industry, due in part to the influence of organizations such as the Federally Funded Research and Development Centers in the United States or the Fraunhofer Institutes in Germany, which (though different models) serve as conduits linking R&D in industry and academia.

6.2.4 Academia-Business Linkages and Receptor Capacity

Successful commercialization is often catalyzed through the interaction of businesses with universities and other research organizations. Industry-university research partnerships and collaborations ensure that businesses are aware of commercially relevant research activities and trends and can capitalize on key advances when they occur. They also ensure that there are channels for communicating business needs to researchers in academia. This is the inspiration for programs such as Canada's federal Centres of Excellence for Commercialization and Research (CECR) program or the Business-Led Networks of Centres of Excellence (BL-NCE) and publicly supported research grants that seek to foster such partnerships by requiring industry involvement, such as NSERC's Strategic Partnership Grants and related programs.

57 The Panel noted one possible exception to this fact. Faculty contracts at U.S. universities in some disciplines may be based on a 9- or 10-month period, whereas 12-month contracts are the norm at Canadian universities. This increases the incentive for U.S. researchers under shorter contracts to seek supplementary income with the private sector, and may contribute to the perception that Canadian academic researchers are less open to industrial research collaborations than their U.S. counterparts.

University TTOs are often in the position of seeking to "push" new technologies into the market. Success, however, often depends on the extent of the *receptor capacity* in businesses (i.e., businesses' ability to develop and commercialize research findings based on their R&D-related assets and managerial and strategic capacity). Larger, R&D-intensive industries often play a critical role in "pulling" new technologies to market (Niosi, 2008; CCA, 2009). These firms have a strategic orientation towards developing new technologies and often maintain robust partnerships and collaborations with university-based researchers. As noted in *Innovation and Business Strategy: Why Canada Falls Short*, "the implication is that commercialization of university research is more likely to occur if the surrounding business environment is rich in firms that are committed to S&T-based innovation as a major business objective — i.e., more 'market pull' is needed in Canada to complement 'research push'" (CCA, 2009). Box 6.3 presents alternative approaches of creating linkage between academia and the private sector.

Box 6.3
Open Science: An Emerging Approach to Create New Linkages

Open Science is an umbrella term to describe collaborative and open approaches to undertaking science, which can be powerful catalysts of innovation. This includes the development of open collaborative networks among research performers, such as the private sector, and the wider distribution of research that usually results when restrictions on use are removed. Such an approach triggers faster translation of ideas among research partners and moves the boundaries of pre-competitive research to later, applied stages of research. With research results freely accessible, companies can focus on developing new products and processes that can be commercialized.

Two Canadian organizations exemplify the development of such models. In June 2017, Genome Canada, the Ontario government, and pharmaceutical companies invested $33 million in the Structural Genomics Consortium (SGC) (Genome Canada, 2017). Formed in 2004, the SGC is at the forefront of the Canadian open science movement and has contributed to many key research advancements towards new treatments (SGC, 2018). McGill University's Montréal Neurological Institute and Hospital has also embraced the principles of open science. Since 2016, it has been sharing its research results with the scientific community without restriction, with the objective of expanding "the impact of brain research and accelerat[ing] the discovery of ground-breaking therapies to treat patients suffering from a wide range of devastating neurological diseases" (neuro, n.d.).

The low levels of business R&D in Canada documented in Chapters 2 and 4 are consistent with a lack of receptor capacity in the private sector. The commercialization of research advances is likely hindered by a general lack of R&D activity in firms, as well as a lack of strategic capacity for developing business strategies based on R&D and innovation. Evidence on the extent of academia-business R&D linkages, however, is mixed. Industry currently funds 7.8% of the R&D undertaken in the Canadian higher education sector. This figure is high by international standards and above the OECD average of 6.2% (Figure 2.4). A deliberate federal policy emphasis on encouraging partnerships has also increased the number of academia-industry research partnerships in Canada, though it does not appear to have increased the flow of research funding originating from industry. Patterns in R&D connectivity between industry and the higher education sector vary by type of institution, and Canada's colleges and polytechnics may be better suited in this regard due to their orientation towards collaborating with local businesses and focusing R&D projects on identified client needs.[58] In general, the amount of industry R&D funding for research taking place in universities and colleges, coupled with increasing numbers of partnerships, does not suggest a deficit of connectivity between industry and universities in Canada relative to other OECD countries.

6.2.5 University Intellectual Property Policies

In Canada, the IP policy regime is highly decentralized (Hepburn & Wolfe, 2015). University IP policies vary by institution and differ based on whether patents are creator-owned or university-owned, and on the shares of commercialization revenue allocated to the researcher and the institution. The University of Waterloo, for example, has an IP policy placing few restrictions on researchers and awarding them ownership of the IP. This decentralized approach stands in contrast to the situation in the United States, where the federal *Bayh-Dole Act* of 1980 created a unified framework for U.S. universities based on shared rights to IP emerging from university research, thereby allowing recipients of federal funding for research opportunities to commercialize their work (Hepburn & Wolfe, 2015).

The diversity of IP policies in Canada has engendered equally diverse views on their design and effectiveness (Kenney & Patton, 2011). There is no consensus or base of evidence on which to single out a particular model as superior. Many U.S. institutions experienced increasing commercialization activity throughout the 1980s and 1990s and some analyses of the impact of the *Bayh-Dole Act* have concluded that it effectively accelerated research commercialization (Tseng

58 However, the capacity of colleges and polytechnics to deliver industry-applied research is not uniform and is still developing, except in places such as Quebec where the Centres collégiaux de transfert de technologie have been doing this for almost three decades.

& Raudensky, 2015). However, it has also been pointed out that university patenting activity at many universities was already on the rise in the United States prior to the passage of the *Bayh-Dole Act* (Mowery *et al.*, 2004). Understood in this context, the Act may have abetted a shift towards IP generation that was underway rather than uniquely precipitating the subsequent increases in patenting activity. In Canada, advocates often attribute the University of Waterloo's success in generating an entrepreneurial climate in part to its more laissez-faire IP policy. Others, however, question whether such a model would be effective if adopted in another context (CCA, 2009).

The impact of IP policies on commercialization success may often be dominated by other factors, as is demonstrated by divergent records of success among universities with similar policies. Attributing research commercialization success (or failure) to specific IP policies is consequently difficult. The effectiveness of different policies, and their respective reliance on TTOs, may also vary by research field. In fields such as biotechnology and the life sciences, where patents (and sometimes suites of complementary patents) can play a key role in determining the value of a technology, centralized models of commercialization through TTOs may be more appropriate (CCA, 2009). As Mowery *et al.* (2004) note, "[s]urveys of industry R&D managers during the 1980s and 1990s consistently suggest that patents and licenses are less important than other channels for knowledge flow and interaction with university researchers (for example, faculty publications or conference presentations) in all fields, including the biomedical sciences."

Given that most Canadian universities adopted policies broadly similar to those of U.S. institutions following the introduction of the *Bayh-Dole Act* (Trosow *et al.*, 2012), varying characteristics of university IP policies in Canada are an unlikely explanation for lower rates of research commercialization. Universities, however, could play a more significant role to help Canada's firms and industries compete in a commercial landscape where IP assumes an increasingly strategic role. Barriers continue to impede firms in their efforts to access patents held by universities, including a lack of incentive to develop licensing agreements given that Canadian post-secondary institutions are hesitant to resort to litigation to defend their IP (Rooksby, 2013). According to Bawa (2017), universities could explore alternative ways of managing patent portfolios that would more effectively allow Canadian firms to access these portfolios for both defensive and offensive purposes, though this may require relinquishing expectations about IP as a source of revenue. Universities could establish a third-party patent aggregator set up for this purpose, making patents available to Canadian firms for defensive purposes.[59] Alternatively, Canada could follow South Korea, France, Taiwan, and Japan in establishing a sovereign patent fund, dedicated to supporting national economic objectives by pooling IP (Bawa, 2017).

Post-secondary institutions, with support from government, could also do more to help Canadian entrepreneurs, firms, legal professionals, and university administrators develop the skills and knowledge needed to compete in the commercial landscape where IP can be a decisive factor. Jim Balsillie has repeatedly argued that Canada "needs to reorient both [its] domestic and [its] geopolitical engagements to ideas commercialization, particularly in the complex, predatory and evolving realm of intellectual property rights management," (Pohlmann, 2014). The Canadian International Council also found that "the majority of Canadian start-ups simply don't know what they are doing when it comes to IP strategy and IP management [...] partly because Canada's education system is not grooming IP coaches to help them map out a strategy" (Mazurkewich, 2011). These observations have led to calls for universities and governments to support new initiatives dedicated to developing the advanced IP management skills required to compete in a global innovation-oriented economy. They have also led to increased scrutiny of the IP components in international trade agreements, where the stricter protections that are often called for by larger economies such as the United States may not always be in Canada's best interest (Blit, 2017).

6.2.6 Researchers, Skills, and Mobility

A wide range of skills contribute to innovation. These include scientific and technical skills, business skills, and soft skills such as communication and teamwork (OECD, 2011b). In Chapter 2, the Panel reviewed key indicators relating to Canada's population of researchers. This evidence does not suggest that Canada suffers from a general deficit of research talent or skills. Canada's population is highly educated, and the number of researchers per capita in Canada is comparable to that of its peers (OECD, 2016a). The number of doctoral graduates in science and engineering is also increasing, though Canada's output remains modest relative to other OECD countries. Canada's primary and secondary education systems also continue to perform well in international assessments, with Canadian students ranking highly on tests of science and mathematics (STIC, 2015). *Some Assembly Required: STEM Skills and Canada's Economic Productivity* also found no evidence of national skills shortages in Canada in science, technology, engineering, or mathematics

59 Some universities are already moving in this direction. Bawa (2017) notes: "The University of Ottawa and École de Technologie Supérieure have joined an international collective of universities that is 'committed to transferring as much IP into commercial use' as possible by making it available for free and based on simplified and balanced agreements."

(STEM), though localized skill shortages or gaps may exist (CCA, 2015a). The report concluded that "the source of Canada's productivity problem is not a shortage of advanced STEM skills" (CCA, 2015a). That finding was echoed by a recent survey of Canadian technology sector CEOs and other stakeholders, who did not report any substantial shortage of scientific or technological talent in Canada (Lazaridis Institute, 2016).[60]

Researcher mobility is another key channel whereby new ideas may be transmitted to industry and subsequently commercialized. According to the *State of the Nation Report 2014*: "[k]nowledge can be transferred informally, 'on two feet,' through the complex, organic and constantly shifting movement and interplay of people" (STIC, 2015). In regions such as Silicon Valley, frequent movement of researchers between universities and industries is thought to be a contributing factor in catalyzing knowledge transfer and the formation of new ventures. This logic also justifies the co-location of industry and university facilities through university research parks. However, while international researcher mobility has been studied in Canada using bibliometric databases (CCA, 2012a), the Panel was unable to find studies or indicators allowing comparison of cross-sectoral researcher mobility in Canada and other countries.

6.2.7 Assessing Rates of Technological Innovation

Technological innovation, through the creation of new products or processes, is the ultimate outcome of many forms of knowledge transfer. While few indicators measure rates of innovation directly, data from internationally comparable innovation surveys can also be used to analyze innovation performance across industries and countries.[61] Two comprehensive surveys of innovation in firms have been conducted to date in Canada, one in 2009 and the other in 2012 (StatCan, 2017b). These surveys centre on questions about whether firms have innovated within the past three business years. More specifically, firms are asked to report whether they have introduced product, process, marketing, or organizational innovations.

Canada compares more favourably to other countries on survey data of this type than might be expected, particularly when it comes to SMEs (Figure 6.4). In 2012, 68% of SMEs and 78% of large firms reported having recently introduced an innovation of some type (OECD, 2015a). Among countries with comparable

60 The perceived adequacy of Canada's supply of advanced STEM skills in the labour market, however, may also reflect depressed demand for these skills given the relative lack of R&D activity in the Canadian business sector.

61 While designed to be internationally comparable, cross-country comparisons using these survey results may still be limited due to differences in innovation survey methodologies and country-specific response patterns. See Mairesse & Mohnen (2010) and OECD (2009) for more details on survey methodology and comparability.

data in the OECD, Canada ranked 3rd by this measure for SMEs, and 17th for large firms (OECD, 2015a). Rates of innovation among large firms, however, are relatively consistent across countries, with 75 to 90% of firms in most countries reporting the introduction of some innovation. Canada's rates of product and process innovation mirror this pattern. Among SMEs, Canada ranked 4th out of 34 countries in rates of product and process innovation (STIC, 2015). Among larger firms, however, Canada ranked 19th by the same measure (STIC, 2015). One interpretation of these data would be that Canada does not underperform its peers when it comes to rates of technological innovation overall, as smaller firms are reporting high levels of product and process innovation. However, larger firms appear to lack a strategic focus on technological innovation, which may reflect market dynamics as much as research commercialization performance.

6.3 BARRIERS TO TRANSLATING TECHNOLOGICAL INNOVATION INTO WEALTH CREATION

Once technological innovations have been developed, their evolution and social impact depend on commercial forces. Firms may fail to achieve market success with innovative products for a range of reasons including, but not limited to, the economic context and structure of the economy, financing availability, the entrepreneurship environment, the quality of management and skills, and the strategic orientation and positioning of business and their abilities to grow to scale and access foreign markets. This section explores the ability of Canadian firms to translate innovations into commercial success and, broadly based, economic benefits.

6.3.1 The Macroeconomic Environment and Tax Incentives

Canada has no obvious deficit when it comes to the macroeconomic environment and framework conditions for supporting innovation. Inflation is low and stable, public debt levels[62] and fiscal deficits are comparatively low, and the tax environment is competitive, with Canada now having the lowest corporate tax rate among G7 countries. Canada is also generally recognized as a relatively open economy, though protection from competition has been identified as a potential damper to innovation in some sectors (CCA, 2009; OECD, 2016b). On balance, however, little evidence suggests that any aspect of the macroeconomic context can explain Canada's long-standing underperformance in business R&D and below average productivity growth.

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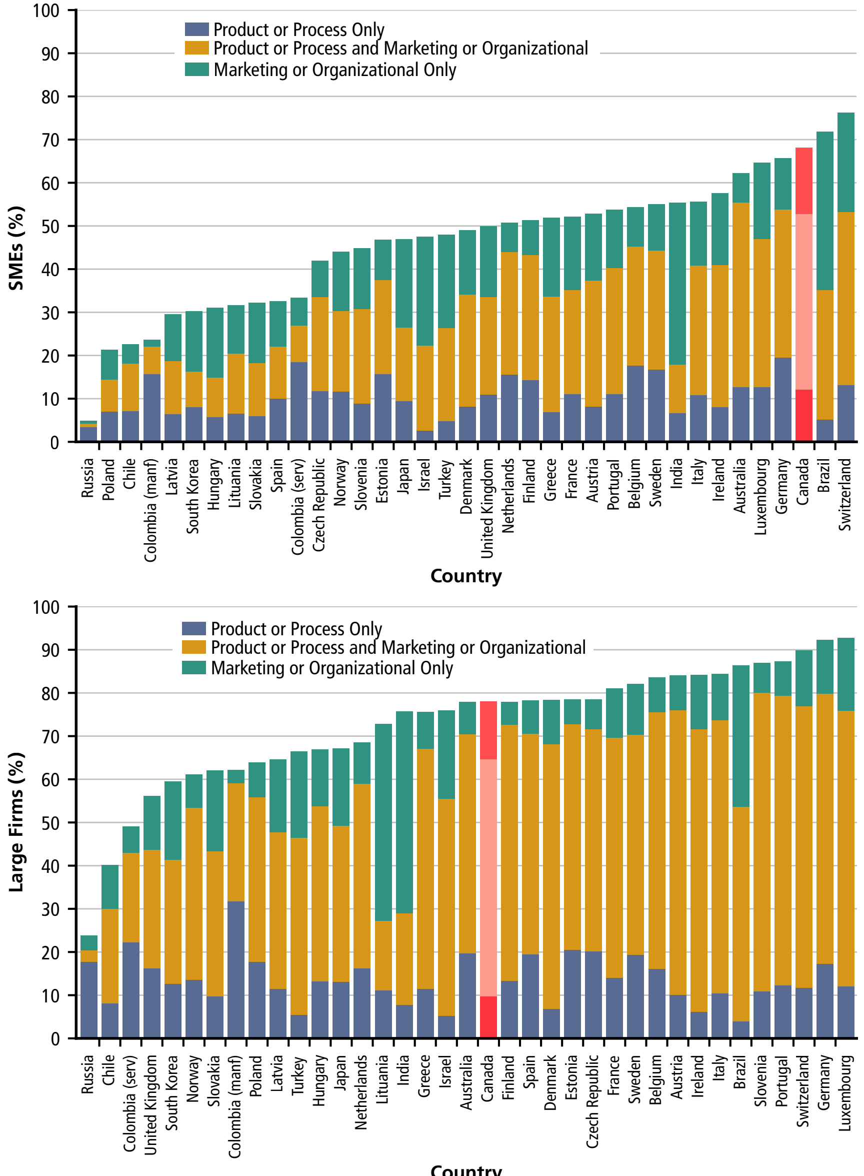
62 Private debt levels, however, are increasing and have been identified as a potential threat to financial stability when coupled with the rapid escalation in house prices in some regions (OECD, 2016b).



Data Source: OECD, 2015a

Figure 6.4

Innovation Performance in Canada and Selected Countries, 2010–2012

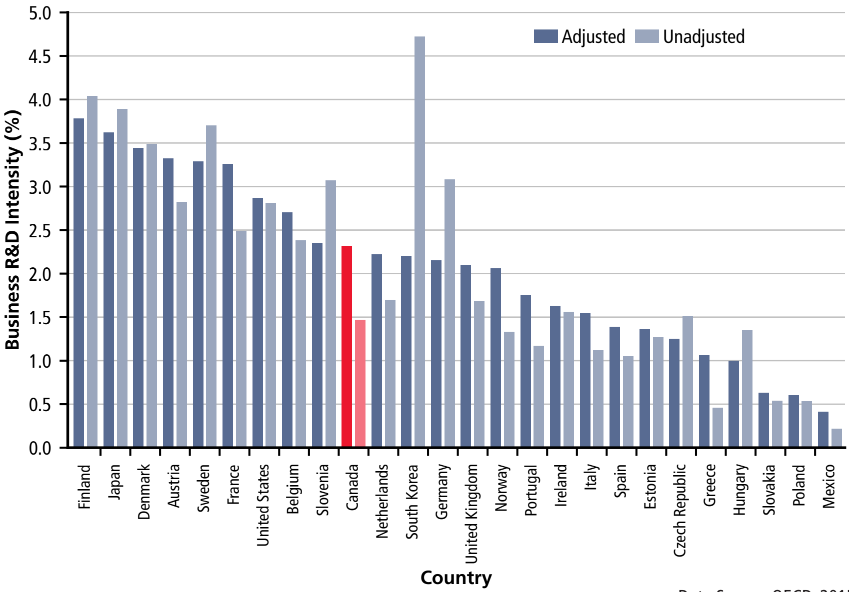
The figure shows the percentage of firms reporting the introduction of product, process, organizational, and marketing innovations over the past year, for both SMEs (top) and large firms (bottom). By this measure, Canada's SMEs report being highly innovative relative to firms in other OECD countries. However, Canada's larger firms are less competitive. SMEs are defined as having fewer than 250 employees, while large firms have 250 or more employees. International comparability, however, may be limited due to differences in innovation survey methodologies and country-specific response patterns.

Canada also provides a relatively generous amount of support to business R&D through the Scientific Research and Experimental Development (SR&ED) tax credit. Canada ranks sixth internationally in the overall amount of tax support provided by R&D credits; however, many countries' R&D tax credits have become more generous in recent years. In response, concerns have been raised that Canada may not remain competitive (Deloitte, 2016). Canada's R&D tax subsidy rate for large firms in particular has declined compared with other OECD countries and now ranks 14th in the OECD (Deloitte, 2016). According to OECD analysis, the R&D tax subsidy rate in Canada for large, profitable firms is less than half of the rate in leading countries such as France, Spain, Portugal, and Ireland (OECD, 2015a). However, it is worth noting that the countries with the most generous R&D tax credits are not the same as the countries with the highest levels of business R&D expenditures. The tax subsidy rate for small firms remains generous in comparison, with Canada ranking fourth by this measure.

Compared with many countries, Canada's overall support for business R&D is heavily weighted towards indirect support provided through SR&ED and the tax system rather than direct support through grants and procurement. R&D tax credits account for 85% of total public support for business R&D in Canada, the third largest share in the OECD (OECD, 2016d). This has caused some to question the effectiveness of a policy mix weighted in favour of tax credits (see Creso, 2016). SR&ED has also been called a "relatively blunt instrument" for supporting young, high-growth R&D-intensive companies, and a shift towards more dedicated funding programs could result in a higher net economic benefit (Secretariat to the Review of Federal Support to R&D Expert Panel, 2011). Research suggests that, in Canada, the firms that have done the best over time have often benefitted from SR&ED tax credits as well as other forms of direct support (Bérubé & Therrien, 2016).

Industrial Structure

Canada's economic reliance on natural resource industries, which tend to be less R&D intensive, is often advanced to partly explain lower R&D investment. In recent years, global economic conditions also have prompted a structural shift and changing terms of trade in the Canadian economy, away from tradable manufactured goods and towards exhaustible natural resources. This shift is unfavourable to the development of more R&D-intensive sectors and industries (Bibbee, 2012). Decompositions of industrial R&D intensity by industry and sector suggest that the structure of the economy cannot entirely explain lower levels of business R&D investment in Canada (CCA, 2009, 2013b). However, accounting for Canada's industrial structure makes a substantial difference in international comparisons. Once industrial structure is factored in, Canada's business R&D intensity is near the OECD average (Figure 6.5). Canada benefits more from this adjustment than any other OECD country. This is consistent with findings reported in Chapter 4, particularly that Canada's R&D is highly concentrated in less R&D-intensive industries relative to other OECD countries. Conversely, some leading countries, most notably South Korea, see a major decline in their R&D intensity once the industrial composition of their economy is taken into account.



Data Source: OECD, 2015a

Figure 6.5

Business R&D Intensity Adjusted for Industrial Structure, 2013

The industrial composition of an economy affects its R&D intensity, as some industries are more R&D intensive than others. Countries with large primary resource industries, in particular, have lower levels of R&D spending, and this is the case in Canada. Once industrial structure is adjusted for, Canada's business R&D intensity is near the OECD average and above some leading R&D spenders such as South Korea. Business R&D intensities are shown as a percentage of value added (rather than as a share of GDP), as R&D expenditures are typically assigned on the basis of value added according to the principal industrial activity. See OECD (2015a) for methodological details.

Corporate Profitability

Another factor potentially underlying low rates of R&D investment in Canada is the relative profitability that Canadian industries have enjoyed under current strategies. Canada's economic performance has been robust in comparison with many OECD peers, driven by relatively high employment growth and strong demand for exports, despite lower productivity growth and investment in R&D

(CCA, 2013b). Past research has also found that Canadian firms on average have appeared to face less competitive pressures than those in the United States, and that corporate profitability before taxes was higher in aggregate (CCA, 2009). Robust growth and weaker competitive pressures may have weakened the incentives for investment in business R&D and innovation. Policies sheltering key sectors such as telecommunications and power generation may play a role in dampening innovation alongside competition (OECD, 2016b).

6.3.2 Canada-United States Economic Integration

Certain structural features of the Canadian economy may be linked to comparatively low private-sector investment in R&D. Nicholson (2016) has recently suggested that Canada's deep historical trade relationship with the United States and the "upstream" integration of Canadian firms into North American value chains is a major factor explaining low business R&D in Canada. According to this argument, Canadian firms are prone to operate under a branch-plant mentality, focusing more on resource extraction, processing, assembly, etc., and less on the development of sophisticated end-products. This pattern is evident in Canada's resource industries (which often focus on raw or lightly processed goods), as well as other key industries where major Canadian firms are often U.S. subsidiaries, such as automotive, chemical, pharmaceutical, ICT, and several large retailers such as Sears and Wal-Mart (Nicholson, 2016). This thesis is consistent with past analyses, which often argued that Canada's foreign subsidiaries were primarily importers of innovation and technology rather than exporters (Britton & Gilmour, 1978).

According to Nicholson (2016), this economic integration has two implications for Canadian businesses and their investment in R&D and innovation. First, Canadian firms often operate within a circumscribed strategic context, with parent companies establishing overarching business strategies and goals for marketing, product development, business organization and practices, and other elements. Canadian subsidiaries then operate within this externally imposed strategic framework. This may result in their prioritizing incremental, operational improvements (i.e., plant-floor innovation) rather than the development or adoption of more novel goods, processes, or technologies. Second, Canadian exporters are often heavily focused on intermediate goods or services provided as part of integrated, continental value chains. This makes Canada stand apart from other small to mid-sized trading nations such as Scandinavian countries, Netherlands, Switzerland, and South Korea, where export markets are more diverse and more focused on providing goods to final consumers. The result is that, within integrated North American supply chains, most end-user-focused innovation occurs in the United States rather than in Canada (Nicholson, 2016).

Thus, Canada's unique trading relationship with the United States — although beneficial to Canada economically for many decades — has helped create conditions in industry that dampen domestic investment in R&D and limit Canada's ability to capitalize on research advances emerging from university and government research facilities. Nicholson (2016) also notes that, while this situation has so far not prevented Canada's economy from achieving comparatively high growth rates relative to other G7 and OECD countries, global trends have the potential to disrupt Canada's current low-innovation equilibrium. These trends include the rise of emerging economies in Asia, the development of new transformative technologies, and an increasing emphasis on environmental sustainability. An additional, emerging factor destabilizing this relationship is uncertainty surrounding the North American Free Trade Agreement (NAFTA), given current negotiations. These trends may force a period of economic adaptation in Canada and the implementation of more innovation-focused business strategies.

Some recent evidence suggests that such a readjustment may already be underway. Wolfe (2017) observes that the share of foreign-controlled R&D in Canada is increasing again. As discussed in Chapter 4, the share of foreign-controlled business R&D in Canada rose from 30% in 2000 to 37% in 2013 (Figure 4.6). MNEs now appear to be actively seeking to leverage Canada's R&D capabilities, increasingly perceiving Canada as a source of R&D assets and talent that can contribute to new product development and feed into global sales and distribution models. This represents a shift away from their traditional strategy of centralizing R&D operations in or close to their home markets (Wolfe, 2017). A prime example is the decision by General Motors to significantly expand its R&D operations in Ontario in 2017 (GM Canada, 2016).

6.3.3 Entrepreneurship

Canadian businesses have a reputation for being risk-averse (Deloitte, 2012, 2017; KPMG Enterprise, 2016). However, when it comes to entrepreneurial activity itself, this conservative reputation is not borne out in recent data from international surveys and rankings. Based on evidence drawn from the Global Entrepreneurship Monitor (GEM), Canadians are highly entrepreneurial. According to Langford *et al.* (2015):

> Canada has the highest rate of early stage entrepreneurship among the major developed countries in the World Bank category on innovation driven economies, with 14.7% of the adult population between [ages 18 and 64 having] undertaken a business start-up in the last 3 years or are operating a new business less than 3.5 years old. Australia (12.8%) and the U.S. (11.9%) follow.

In a previous Conference Board analysis of the data, Canada ranked third among the peer countries identified on this measure, trailing only the United States and Australia (CBOC, 2015). Canada also ranks third (behind the United States and Switzerland) on an entrepreneurship index compiled by the Global Entrepreneurship and Development Institution, based on survey data assessing entrepreneurial attitudes and abilities, as well as indicators of the economic infrastructure (GEDI, 2017). Cross-country surveys and rankings also point to a relatively supportive environment for starting new ventures. According to the World Bank Ease of Doing Business Survey, Canada ranks second in the world when it comes to the ease of starting a new business (World Bank, 2017). In addition, according to the *2017 Global Start-Up Ecosystem Report*, Toronto–Waterloo and Vancouver both rate among the top 20 areas in the world to start a technology business (Startup Genome, 2017). Canadian entrepreneurs now also benefit from an increasingly broad and diverse range of start-up assistance organizations (Box 6.4).

Box 6.4
Start-Up Assistance Organizations in Canada

In Canada, 146 start-up assistance organizations (SAOs) currently provide support to entrepreneurs in various stages of creating their businesses. These include 79 business incubators, 29 business accelerators, 21 commercialization organizations, and 17 hubs (DEEP Centre, 2015). SAOs may be run by private entities, governments, universities, or not-for-profit organizations such as hospitals (DEEP Centre, 2015). They are over-represented in Ontario (which hosts 50% of all SAOs), followed by British Columbia (19%), Quebec (17%), and Alberta (10%).

The DEEP Centre’s analysis of 20 leading Canadian accelerators and incubators shows that these organizations provide over $1.7 billion in follow-up investments, serve about 1,500 clients (with an average investment of about $500,000), and are responsible for the creation of 10,000 jobs (DEEP Centre, 2015). However, in the absence of a nationwide standardized reporting framework for activity and outcomes, it is not possible to conclude much about the economic impact of SAOs in Canada. The analysis also notes that accelerators and incubators still lack distinct success stories (DEEP Centre, 2015).

One model that has attracted increasing attention in recent years is the Creative Destruction Lab (CDL) housed at the Rotman School of Management at the University of Toronto. CDL connects promising innovators and entrepreneurs with access to experienced professionals who can help them navigate challenges in moving from

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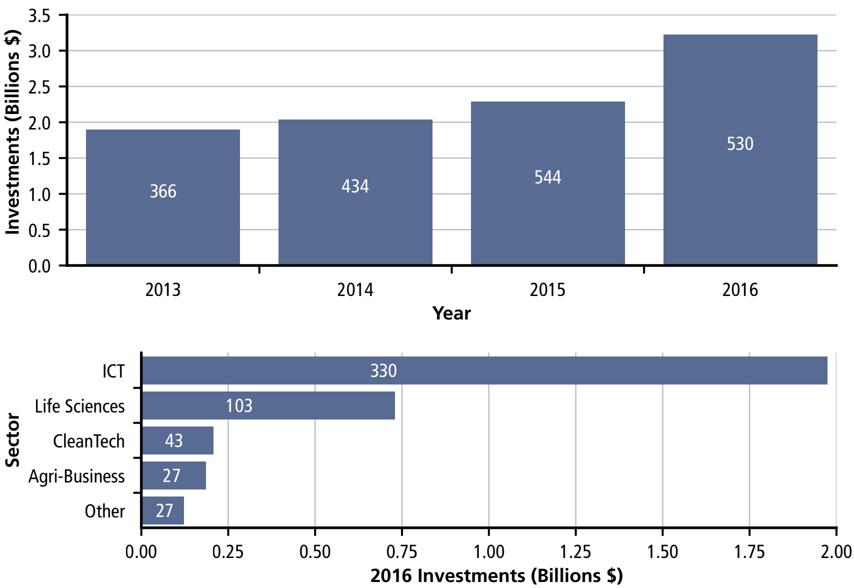
the pre-seed to seed stage (CDL, 2017). The program also provides participants access to workshops with faculty at the Rotman School of Management, legal and accounting services from leading providers, and access to financing opportunities through coaches and other institutional and private investors. CDL has expanded since its inception and now runs programs in Toronto, Vancouver, Halifax, Montréal, and Calgary, and has a dedicated program for machine learning start-ups. Graduates of the program are collectively now valued in excess of $600 million (Silcoff, 2017).

OECD data show that Canada's rates of new firm entry increased between 2011 and 2014, and that it is one of only a few OECD countries with rates higher than pre-financial crisis levels (OECD, 2016c). A Conference Board of Canada analysis, however, found that rates of *enterprise entry* (the ratio of new firms to existing firms) are low in Canada relative to peer countries. Canada's rate of 7% in 2012 was roughly half that of leading countries such as Finland and the United Kingdom (CBOC, 2015), though this figure is roughly consistent with the rate of enterprise entry reported in the United States (Hathaway & Litan, 2014). Both Canada and the United States have experienced a long-term decline in rates of enterprise entry (Hathaway & Litan, 2014; CBOC, 2015). The causes of this decline in North America are unclear, but it has raised concerns, particularly in the United States, that the dynamism of the business sector is decreasing over time, threatening future innovation and productivity gains. In Canada's case, the OECD has also noted that Indigenous peoples and women remain under-represented among Canadian SME founders (OECD, 2016c).

6.3.4 Venture Capital Financing

The CCA report on innovation in Canada (CCA, 2009) identified a lack of depth in Canada's venture capital (VC) markets as a potentially significant barrier to innovation. At the time, Canada's VC flow was low relative to most countries, especially the United States. However, in this domain, Canada has seen a major improvement in recent years, with increasing investment levels and numbers of deals. The year 2016 marked the seventh straight year of VC growth and the largest since 2001 (Pinto *et al.*, 2016). VC investment was up by 41% from 2015, yielding 530 deals totaling $3.2 billion in investments (Figure 6.6). Increasing VC investment in Canada, coupled with failing investment in many European countries, has catapulted Canada from one of the weakest countries to one of the strongest (CBOC, 2015). Canada now ranks behind only the United States and Israel in VC investment as a share of GDP (Figure 6.7).

Research from the Conference Board of Canada identifies two key factors behind this reversal (Munro, 2015). First, there was a strong increase in U.S.-funded VC in Canada. Historically, foreign firms accounted for roughly 30% of Canada's annual VC investment. By 2014, however, the United States alone accounted for over 37% of the total. Between 2012 and 2013, increasing investment from the United States accounted for over 90% of the increase in investment in Canada. Second, while the VC situation in Canada improved following the global financial crisis, it deteriorated substantially in many countries. Several peer countries experienced large reductions in VC investment, including Australia (–67%), Belgium (–65%), and Norway (–61%). In this more competitive post-recession environment, Canada's relative ranking improved as Australia and European countries found VC funding increasingly scarce.



Data Source: Pinto *et al.*, 2016

Figure 6.6

VC Investment Trends in Canada, 2013–2016

VC investments have grown substantially in Canada in recent years, rising to over $3 billion in 2016. These investments have been mostly concentrated in the ICT sector in British Columbia, Ontario, and Quebec. Continuing a long-standing trend, the majority of Canada's VC deals in 2016 were for new ventures in the ICT industry and the life sciences. The numbers in the bars on both graphs represent the number of deals.

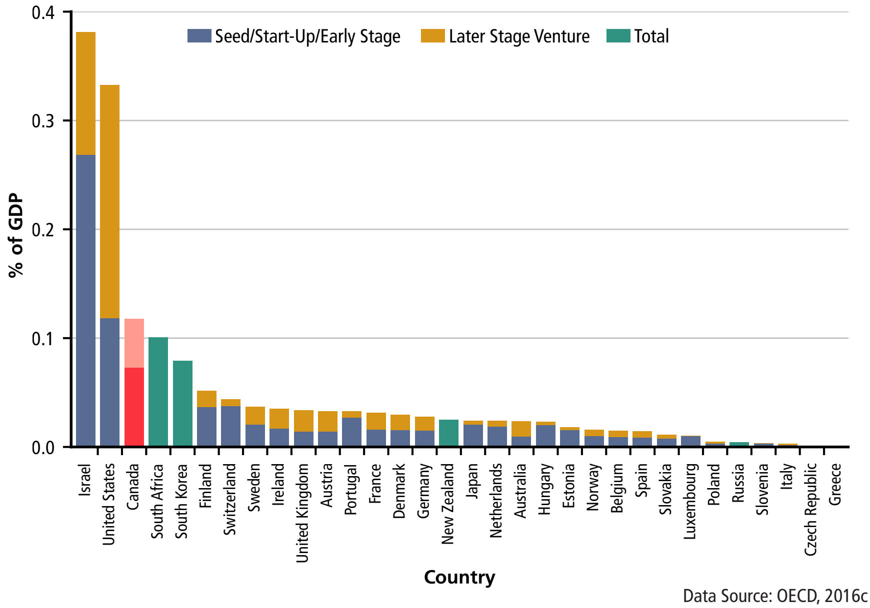


Figure 6.7

VC Investment as a Percentage of GDP, 2015

Canada's level of VC investment has increased in recent years and, expressed as a share of GDP, now exceeds that of all other countries except for the United States and Israel.

The federal government's creation of the Venture Capital Action Plan (VCAP) in 2014 has also played a role in supporting the expansion of risk capital availability in Canada. Designed to establish and recapitalize large-scale, private-sector-led funds of funds, VCAP has leveraged $340 million from the federal government into what will be a total of over $1.4 billion in new VC investment (CVCA, 2017).

An ancillary benefit occurring alongside increasing VC flows is that Canadian firms also gain better access to external management expertise (Munro, 2015). However, Canada's relative performance also continues to be strongly determined by its position in the North American market. Here, Canadian firms may still be at a disadvantage relative to those in the United States. As Munro (2015) notes: "Even as Canada has vaulted into the top tier of VC investment destinations, firms in the United States continue to attract VC at higher rates and see deals that are twice the size of average deals for Canadian firms."

6.3.5 Firm Growth, Job Creation, and Market Dynamics

In 1999, Google was an internet start-up operating out of a garage with eight employees. Five years later, Google had some 3,000 employees and, by 2010, over 24,000 full-time employees (Dixon & Rollin, 2014). In Canada, BlackBerry was on a similar trajectory, growing from 200 employees in 1998 to 17,000 in 2012 (Dixon & Rollin, 2014). Google and BlackBerry are examples of what economists call *high-growth firms*.[63] Research has consistently demonstrated that these firms play a powerful role in the economy, accounting for large shares of overall job creation and associated economic benefits. In a seminal study, Birch (1979) showed that small, rapidly growing firms in the United States were the source of the majority of new jobs created. Subsequent research has confirmed this pattern in many other contexts. Storey (1994) found that 4% of firms created 50% of the jobs. In the United Kingdom, a Nesta report based on similar research found that 6% of firms were responsible for 49.5% of all jobs created between 2002 and 2008 (Nesta, 2009). Daunfeldt *et al.* (2015) found that, in Sweden, the fastest growing 6% of firms created 42% of new jobs between 2005 and 2008. The same pattern holds in Canada. A study from Industry Canada found that high-growth firms were responsible for nearly 1 million of 1.8 million net jobs created over a 15-year period (Parsley & Halabisky, 2008). Dixon and Rollin (2014) found that high-growth firms in Canada accounted for 85% of total job creation between 2000 and 2009.

Fortunately, the evidence does not suggest that Canada suffers from an overall lack of high-growth firms relative to other advanced economies. Based on employment, high-growth firms account for between 2% and 6% of all firms for OECD countries (OECD, 2015c). OECD data suggest that Canada is at the upper range of this distribution, with 4.5% of firms in industry qualifying as high-growth firms in 2013 (OECD, 2016c). International comparisons suggest that business dynamics are more volatile in the United States than in Europe, with the former having both a higher share of high-growth and low-growth (negative) firms (Bravo-Biosca *et al.*, 2014). Canada is similar to the United States in this regard. The latest data from the OECD (2016c) show that Canada has a greater proportion of high-growth firms in industry overall, but a lower proportion in the services sector. Canada has a particularly high share of high-growth firms in the construction sector.

63 Methodological differences in how high-growth firms are defined and analyzed mean that studies are not always strictly comparable (Côté & Rosa, 2017). The most common statistical definition used to identify high-growth firms is those with 10 or more employees that have employment growth exceeding 20% per year over at least a three-year period (Coad *et al.*, 2014; OECD, 2015c).

High-growth firms can be located in every industry, however, and economy-wide trends may not accurately reflect firm dynamics in the technology sector. A 2008 study found that most of the top 20 industries by share of high-growth firms in Canada were not knowledge-intensive industries (Parsley & Halabisky, 2008). Critically, while Canada does not appear to lack high-growth firms, young Canadian firms may fail to sustain growth as they mature relative to firms in the United States and Europe. *Gazelles* are the subset of high-growth firms younger than five years old. Canada tends to rank higher relative to other OECD countries on its *gazelle rate* (the share of rapidly growing young firms) than it does in overall high-enterprise growth (OECD, 2011a). This suggests that Canadian firms may fail to sustain higher growth rates as they mature, particularly in comparison to similar firms in countries such as the United States and Israel (Deloitte, 2012). The Business Development Bank of Canada (BDC) has found that the number of Canadian mid-sized firms (with between 100 and 499 employees) declined by 17% between 2006 and 2010 (BDC, 2013), with the steepest decreases occurring in the manufacturing sector and in Ontario.[64] This loss has significant economic implications. While mid-sized firms represent less than 1% of total Canadian firms, they account for 16% of Canada's employment, and generate 12% of GDP and 17% of exports (BDC, 2013).

Additional evidence related to the failure of firms in Canada to grow domestically can be drawn from the aspirations of Canadian entrepreneurs, the large majority of whom intend to exit their business via either an acquisition or merger within the next six years (PwC, 2015). According to a survey of technology entrepreneurs in Canada, only 6% indicated that they planned to eventually take their company public through an initial public offering. In comparison, nearly two-thirds expected their companies to be acquired (PwC, 2015). As the study notes:

> [T]his can create a situation where Canada's innovators begin building products to sell rather than businesses to grow. And for governments making sizeable investments to grow and support Canadian technology and entrepreneurship, the risk is that those funds end up benefiting firms outside Canada [...] While Canada is doing a stellar job of launching new technology ventures, we're not doing very well at building sustainable, innovative businesses.
>
> (PwC, 2015)

64 BDC (2013) hypothesizes that this decline reflects the global shift in manufacturing production towards Asia and the rise of the value of the Canadian dollar over that period, which adversely affected exporters. The result was an overall loss of medium-sized firms and a shift in their composition towards retail, food and accommodation, and business services.

Foreign acquisitions of Canadian start-ups may result in much of the economic benefit derived from an innovation accruing to other countries, primarily the United States. Relative to the case where a firm matures in Canada and grows to become a large domestic employer paying taxes in Canada, Canadian technology start-ups acquired by foreign owners may yield little in domestic benefits (despite representing a rational and profitable exit strategy for the firm's founders). The extent of the economic losses to Canada depends also on the extent to which a firm's activities are relocated after its acquisition. Foreign acquisitions may not always result in a relocation of firm activities, and future growth may continue to occur in Canada. The proceeds from the sale of a business can also be reinvested in Canada, for example, funding other start-ups, thereby still contributing to local economic development.

The economic impact of high-growth firms has led to growing interest among policy-makers (Coad *et al.*, 2014). In Canada, the 2017 federal budget announced the government's intention to create new mechanisms to support "high impact firms" (GC, 2017). However, research suggests targeting support is challenging because it is extremely difficult to identify high-growth firms in advance (Coad *et al.*, 2014). It also shows that government attention may be best focused on ensuring that framework conditions are conducive to their emergence. BDC research has found that high-growth firms in Canada face a number of barriers to growth, including financing, labour, accessing new markets, and management capabilities (BDC, 2015). Financing challenges can become acute when the available mechanisms are simply not responsive enough to meet the needs of firms going through a period of rapid growth (BDC, 2015).

6.3.6 Management Skills and Experience

Previous assessments of Canada's innovation performance have identified a deficit of management skills and experience as an impediment for Canadian firms. A CCA (2009) report found that a significantly higher proportion of managerial employees in the United States, relative to Canada, had university degrees. The proportion of U.S. managers with business degrees was more than double the Canadian level. The report noted that "this gap would be expected to translate to a difference between U.S. and Canadian businesses, on average, in the propensity to be aware of, and to adopt, leading-edge technology and business practices" (CCA, 2009). Another CCA (2015a) report emphasized that STEM skills alone are not sufficient to generate productivity growth, and that "complementary skills, such as communication, teamwork, and leadership, are also important in and of themselves, as well as to maximize the impact of STEM skills."

While internationally comparable indicators related to the availability of managerial skills are lacking, some research has found that deficiencies in Canada's business education programs may place Canadian firms at a disadvantage. A Conference Board of Canada study found that, while Canadian employers generally gave graduates of Canadian management, business, and finance programs high marks for their technical and analytical skills, they felt these employees often needed to improve communication skills and leadership potential (Munro, 2009). Canadian firms and business leaders frequently point to challenges in recruiting people with the right management and business skills. For example:

- BDC research on mid-sized firms found that 45% of those surveyed reported their top internal challenges were employee acquisition and retention, and talent or expertise development (BDC, 2013).
- A 2014 report from the Conference Board of Canada, based on a survey of 169 firms, identified building of the leadership pipeline as a major challenge (Martin *et al.*, 2014).
- In annual surveys of business leaders undertaken by KPMG and the Ivey School of Business, 28% of Canadian business leaders identify talent attraction as their primary strategic challenge, with a further 14% highlighting a lack of capable management as the key factor impeding business growth (KPMG Enterprise & Ivey Business School, 2015).
- A 2015 PricewaterhouseCoopers report found that 14% of Canadian technology-focused start-ups identify recruiting an experienced management team as a key issue (PwC, 2015).

Additional evidence on the severity of these challenges is found in a recent survey of 125 Canadian technology business leaders and stakeholders undertaken by the Lazaridis Institute at Wilfrid Laurier University (Lazaridis Institute, 2016). This study found that 53% of those surveyed felt that a shortage of "experienced management and/or executive talent" was the primary barrier to scaling up, and this was rated as the highest priority challenge across all stakeholder groups surveyed. While STEM skills are perceived as being abundantly available, there is a lack of management competencies in areas such as sales, marketing, organizational design, product design and development, and product management. This shortage was seen as connected to both the immaturity (i.e., a dearth of large, mature R&D spenders with a billion dollars or more in revenue) and the lack of density of the Canadian technology landscape, which makes recruitment more challenging. As noted by the authors:

> Technology talent with scaling experience is thus difficult to attract and, as a result of the lack of anchor firms, insufficiently developed within Canada. The result is an ecosystem that excels at the creation of entrepreneurial ventures but fails to support their evolution into high-growth firms — firms responsible for the majority of net new job growth.
>
> (Lazaridis Institute, 2016)

This gap in experienced management talent was identified separately in a similar study focused on the ICT industry (Sloan & Dale, 2015). That study identified access to talent as a key challenge, specifically to "C-suite talent" (i.e., senior executives such as Chief Executive Officer, Chief Financial Officer, and Chief Information Officer). This finding echoes a report from the Information Technology Association of Canada, which also found that a lack of access to "C-suite talent with experience taking a company from a start-up to a $100M global enterprise" was inhibiting the growth of Canadian technology companies (Gupta, 2012). Managerial skills are particularly lacking when it comes to guiding firms to move into larger markets such as the United States without help from a U.S. VC firm, finding a major partner, or being acquired. Finding on the ground sales and support skills, handling IP and contracts, understanding transfer pricing, doing international accounting, and filing U.S. taxes are often obstacles for smaller Canadian companies with high growth prospects. According to a Canadian CEO who responded to the Lazaridis Institute study:

> It's about finding talent who has seen this show before. Canada has very few of these people as we simply don't have the companies that have gone through high-growth phases. We need a deeper market of people who understand exceptional growth paths and exceptionally dynamic technology markets.
>
> (Lazaridis Institute, 2016)

6.4 CONCLUSION

Canada's combination of high performance on measures of research output and impact and low performance on measures of industrial R&D investment and innovation (such as subpar productivity growth) are viewed as a paradox (CCA, 2013c), frequently prompting the supposition that bottlenecks or barriers must be impeding the flow of Canada's research achievements into commercial applications. This supposition underlies the fourth sub-question in the Panel's charge, which requests an analysis of such barriers. On balance, however, the evidence does not support the premise behind the question. The process of transforming R&D into innovation and wealth creation is complex and multifaceted, making it difficult to definitively point to a single underlying cause of Canada's perceived deficit of innovation. In the Panel's view, Canada's ability to translate research strengths and achievements into technological innovations is not hindered by major systemic barriers. The barriers impeding the translation of technological innovations into wealth creation, however, are more significant.

Table 6.2 summarizes the various factors examined by the Panel and key points of supporting evidence. When it comes to the translation of research into innovation, many of the factors commonly identified cannot persuasively account for overall weakness in Canada's innovation performance compared with other countries. Academia-business linkages appear robust given the extent of cross-sectoral R&D funding and increasing academia-industry partnerships. The educational system is high performing by international standards and there does not appear to be a widespread lack of researchers or STEM skills. Diverse IP policies at universities are also unlikely to explain a divergence in the innovation rates of Canadian and U.S. institutions, though Canadian universities and governments could be more active in aiding companies to compete when it comes to IP management and strategy. While more problematic a decade ago, VC availability in Canada has improved dramatically. On balance, technology start-ups and start-up ecosystems are flourishing in many sectors and regions, thereby demonstrating their abilities to build on research advances to develop and deliver innovative products and services.

Growing these firms into large, mature R&D-intensive businesses presents other challenges. While Canada's macroeconomic framework conditions are conducive to business development, the tight integration of the Canadian and U.S. economies may have circumscribed the ability of many Canadian firms to pursue end-user-oriented innovation strategies that are focused on higher value-added goods and services. Canada's reputation as a supportive environment for entrepreneurs is growing; however, large numbers of these entrepreneurs intend to sell their firms to foreign investors rather than develop them to scale domestically. A major driver of this is the lack of managerial experience and IP skills in Canada required to guide technology firms as they go through periods of rapid expansion into global markets. Canada's R&D tax credits are also more competitive for smaller firms than they are for large corporations, making Canada a better place to start a technology company than to grow one. The result is a deficit of Canadian technology firms developed to scale domestically. Foreign acquisition of Canadian start-ups does not eliminate the economic benefits of these firms for Canada; however, it does limit these benefits depending on the extent to which business operations and future development remain in Canada.

Table 6.2

Key Barriers to Translating R&D to Innovation and Wealth Creation in Canada — Summary Table

Barrier	Significance of Barrier	Trend	Evidence
Barriers in Translating R&D to Innovation			
University Research Commercialization	Medium	—	• Few Canadian TTOs have developed robust commercialization revenue streams. • AUTM data show Canadian universities have technology licensing and income streams below those of U.S. institutions. • Internationally comparable evidence on many other research commercialization indicators, however, is lacking.
Academia-Business Cultural Divide	Medium	—	• Incentive structures, professional priorities, and cultures differ between academia and industry. • This gap may be worse in Canada than in other countries, though there is no definitive evidence.
Academia-Business Linkages and Receptor Capacity	Medium	↑	• Comparatively high rates of industry-financed higher education R&D in Canada suggest well-established academia-business linkages. • The number of cross-sectoral research partnerships is increasing in response to partnership programs from NSERC and other federal agencies. • Low business receptor capacity for new research, however, is due to a lack of large, established corporate R&D spenders.
University IP Policies	Low	—	• IP policies vary by institution, but are often comparable to those in the United States. • Case evidence suggests that different models (e.g., Waterloo, Stanford) can be equally effective in promoting research commercialization. • There is increasing evidence that universities and governments could do more to help Canadian firms compete internationally when it comes to IP management and strategy.

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Barrier	Significance of Barrier	Trend	Evidence
Researchers, Skills, and Mobility	Low	↑	• Canada has relatively high educational attainment in the general population, and high scores on international science and math assessments for students (OECD PISA scores). • The number of STEM PhDs in Canada is increasing, and there is no evidence of a national shortage of STEM skills, though localized skill deficits may exist. • No robust, cross-country evidence exists to assess differences in research mobility across sectors.
Barriers in Translating Innovation to Wealth Creation			
Macroeconomic Environment	Low/Medium	—	• Canada has a stable macroeconomic environment, good fiscal management, low inflation, and competitive corporate tax rates (lowest in G7). • Canada provides moderate to high tax support for business R&D through the SR&ED tax credit. • However, SR&ED's international competitiveness for large firms is much lower than it is for small firms.
Canada-United States Economic Integration	Medium	↑	• Tight integration of supply chains in North America may have led Canadian firms to adopt branch-plant innovation strategies, leaving sophisticated, end-user innovation mostly to U.S. firms. • This may be challenged by global economic, technological, and social trends, thereby disrupting Canada's current low-innovation equilibrium.
Entrepreneurship	Low	↑	• Survey evidence and international rankings find Canadians to be highly entrepreneurial, and Canada to have a positive climate for entrepreneurship. • Canada ranks highly in ease of starting new businesses. • Canada, however, has low rates of firm entry relative to peer countries and lower participation rates for women and Indigenous Peoples in starting businesses.

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Barrier	Significance of Barrier	Trend	Evidence
VC Financing	Low	↑	• Canadian VC has increased significantly in recent years, while VC availability in some peer countries has declined following the global financial crisis. • Canadian firms may still face financing challenges and limitations relative to those in the United States.
Firm Growth and Market Dynamics	High	—	• Canada's share of high-growth firms is comparable with the United States and other OECD countries. • Shares of young, high-growth firms are higher, however, suggesting that Canadian firms may be failing to sustain growth as they mature. • Most Canadian tech start-up founders anticipate selling their firms within six years. • High rates of foreign acquisition of Canadian tech start-ups may result in diminished domestic economic benefits to Canada as later stages of expansion and growth may occur in other countries.
Management Skills and Experience	Medium/High	—	• Canadian business leaders consistently point to challenges involving recruitment of managerial skills and experience. • Specifically, recent survey evidence suggests a lack of Canadian managerial experience and skills needed to grow technology firms to scale domestically while selling into global markets.

The trend column describes the direction to where the barrier is heading. An upward arrow indicates that the barrier is becoming less of an impediment over time. A dash sign indicates that the trend is constant.

7

Conclusions

7 Conclusions

In the 21st century, national prosperity, competitiveness, and well-being are inextricably linked to a country's capacity for R&D and innovation. The world now appears poised on the brink of profound economic, social, and technological shifts as a confluence of advances in digital technologies, biotechnology, networked production processes, and autonomous transportation systems promise widespread benefits, while simultaneously threatening to be a source of significant industrial and societal disruptions. From discoveries in AI and genome editing techniques to behavioural economics and climate science, today's R&D advances will define the contours of society in coming decades. Countries that strategically support R&D and innovation will benefit from coming advances and discoveries. Countries that do not provide such support risk becoming unable to participate in world-leading research and equally unable to reap its eventual social, environmental, and economic benefits. They also risk leaving fundamental insights undiscovered. By shedding light on everything from the forces driving the expansion of the universe to exploring our shared histories, Canada's researchers are gradually expanding our collective stock of knowledge.

Faced with the task of assessing the state of R&D in Canada, the Panel undertook an extensive review of evidence, spanning all aspects of R&D, from investment and infrastructure to publications and patents. The Panel also considered the extent to which Canada's R&D effectively supports innovation and wealth creation. The resulting body of evidence is multidimensional, and not all trends can be easily synthesized into a single, coherent narrative or national story. R&D trends and performance vary by performer, by research field and subfield, and by sector and industry. Some research fields reflect interests and activity of an international community of scholars; others are no less important but address local or regional issues. The data provide an aggregate picture, but often miss specific, niche areas of R&D excellence located in universities, colleges, firms, and research organizations across Canada. It would be impossible for a report such as this to capture comprehensively the complexity and diversity of all research activity across the country. Researchers, research institutions, and policy-makers are encouraged to undertake their own reviews of the wealth of data generated for this study (those presented in this report and in the appendix), and formulate their own questions and insights.

However, reflecting on all the evidence available, the Panel came to seven conclusions about the current state of R&D in Canada:

1) Canada remains a leading global contributor to research, and is making important contributions across a wide range of fields.

Bibliometric and survey evidence assembled by the Panel suggest that Canada remains a leading contributor to research in a wide range of fields. Canada continues to account for a large share of research publications, ranking ninth in the world in publications produced between 2009 and 2014. Growth in Canada's research output is also relatively robust, exceeding that of many developed countries, including France, Germany, Japan, the United Kingdom, and the United States, between 2003 and 2014. Research output in all these countries, however, is increasingly overshadowed by the rapid rise in the number of publications from China. In 2014, China accounted for 22% of the world's total publications (in whole counts) and, given recent trends, it has likely now surpassed the United States as the world's leading producer of research.

Indicators suggest that Canada has held its ground in recent years in research impact. Canada ranks sixth across all countries on a standard measure of citation impact (e.g., ARC score). Canada's international reputation for research excellence also remains strong, with top-cited researchers ranking Canada fourth globally; it is home to world-leading research programs and facilities in many fields. Based on ARC and survey rankings, Canada has retained its leadership in fields identified in the 2012 S&T report. On a composite indicator of research strength based on *magnitude* (Canada's share of world publications in that field), *impact* (ARC scores and ranks), and *growth* (Canada's growth in research output relative to the rest of the world), the fields in the top quartile — areas of comparative strength for Canada — are Visual and Performing Arts, Psychology and Cognitive Sciences, Clinical Medicine, Public Health and Health Services, and Philosophy and Theology. The bottom quartile represents fields in which Canada is less competitive internationally, and includes Engineering, Communication and Textual Studies, Mathematics and Statistics, Enabling and Strategic Technologies, and Built Environment and Design. Taken together, bibliometric and survey data show that Canada continues to produce high-impact research across most fields.

2) Canada's international standing as a leading performer of research is at risk due to a sustained slide in private and public R&D investment.

Canada's current research strengths reflect the outcomes of past investments and the fact that its research infrastructure, facilities, and people have developed over many years. Transformative government investments in research infrastructure and talents, through the Canada Foundation for Innovation, the Tri-Agency, and other departments and agencies, are continuing to pay dividends, supporting world-leading research in facilities nationwide. Canada's current pool of research talent reflects the decades-long process of training new researchers, beginning with a solid foundation in the K-12 system and continuing through advanced education and training.

However, flat or declining research investments by government and the private sector in the past decade now threaten to erode Canada's capacity for producing high-quality research in the future. Canada has seen consistent annual declines in its ranking relative to other OECD countries on business, government, and even higher education R&D expenditures in recent years. It is one of few OECD countries to have seen virtually no growth in national R&D spending over the 10-year period between 2006 and 2015. Data on industrial R&D expenditures, personnel, and related variables indicate a sustained erosion of Canadian research capacity and competitiveness in the private sector. While not yet apparent in data on research outputs and impacts, diminished R&D funding, both in absolute and relative terms, will inevitably be detrimental to the competiveness of Canada's R&D establishment in the future.

3) Canada is not producing research at levels comparable to other leading countries on most enabling and strategic technologies.

When it comes to research on most enabling and strategic technologies, Canada is a follower rather than a leader. With the exception of Biotechnology and several important subfields in Information and Communication Technologies, Canada was not ranked among the top five countries by ARC score for 2009–2014. Canada also accounts for relatively low shares of world research in these areas, and is not competitive with other leading countries in many of them, including Energy, Materials, Nanoscience and Nanotechnology, and Optoelectronics and Photonics. Overall, Canada's level of specialization (i.e., SI score) is significantly below the world average in most of these areas, and its level of impact (i.e., ARC score) is approximately on a par with the G7 average. These results are echoed in *Canada's Fundamental Science Review* (Advisory Panel for the Review of Federal Support for Fundamental Science, 2017), which also concludes that Canada's research potential is not being realized in areas such as AI and Regenerative Medicine despite pioneering work in these fields. Such findings are concerning; they demonstrate a failure to develop what could have been areas of R&D advantage in Canada, yielding significant benefits to the economy and society. While renewed support for Canadian AI research may reverse these trends in one field, Canada risks becoming marginalized in other areas of technological development if it does not support research efforts at levels comparable to other leading countries.

4) Canadian research is comparatively less specialized and less esteemed in the core fields of the natural sciences and engineering.

Canada's international research reputation (based on survey data) is lowest in several core fields of the natural sciences such as Mathematics and Statistics, Physics and Astronomy, Chemistry, and Engineering. Not coincidentally, these are also research fields in which Canada has a low specialization, accounting for fewer of the world's research publications than would be expected, although the impact of research is high in many subfields such as Astronomy and Astrophysics. This poses another threat to Canada's R&D potential, namely the ability to pivot towards what will become the frontiers of research in the natural sciences and engineering. In the same way that general cognitive skills and capabilities (e.g., literacy, numeracy, critical thinking) ensure individual adaptability, research capacity in core areas of the natural sciences contributes to the flexibility of the research base, fostering knowledge, skills, and experience that can be applied in a wide variety of research contexts and problems. A lack of specialization in core scientific disciplines increases the likelihood that Canada may be unable to participate meaningfully in the emerging research areas of the future or to fully benefit from the technologies that such research may yield.

5) Canadian industrial R&D spending is declining and concentrated in industries that are intrinsically less R&D intensive. Despite poor overall performance, Canada has pockets of R&D strength across several industries.

Compared with G7 countries, Canada's portfolio of R&D investment is more concentrated in industries that are intrinsically less R&D intensive. About 50% of Canada's industrial R&D spending is in high-tech sectors (including industries such as ICT, aerospace, pharmaceuticals, and automotive) compared with the G7 average of 80%. Canadian BERD intensity is also below the OECD average in these sectors. By contrast, for low and medium-low tech sectors, industrial R&D is less important to overall business strategy. Canada excels in low-tech sectors (including oil and gas, forestry, machinery and equipment, and finance), investing sustainably more than the G7 average and in some cases at a much higher intensity. Overall, this spending pattern reflects Canada's long-standing industrial structure and patterns of economic activity.

The Panel measured industrial R&D strengths in much the same way as it measured industrial R&D spending across countries: by magnitude, intensity, and growth. First, between 2011 and 2015, seven Canadian industries invested more than $1 billion in R&D spending per year: scientific R&D services, computer systems design, aerospace manufacturing, information and cultural industries, wholesale trade, oil and gas extraction, and communications equipment manufacturing. Collectively, these seven industries accounted for more than 60% of Canada's industrial R&D during the period. Second, only 10 of Canada's 45 industries invested more than 5% of revenue in industrial R&D between 2009 and 2013, including in scientific R&D services (30.1%), communications equipment manufacturing (17.3%), computer systems design (8.1%), and aerospace (5.6%). Third, growth in industrial R&D spending was more widely distributed between 2006 and 2015, with 18 industries growing faster than the OECD average (2.6%) led by metal manufacturing, transport equipment, and retail trade. Six of the big seven industries grew between 2006 and 2015 with the exception of communications equipment manufacturing.

Based on a composite indicator of magnitude, intensity, and growth, the Panel classified four industries of R&D strength:

- Scientific research and development services
- Computer systems design
- Communications equipment manufacturing
- Aerospace products and parts manufacturing

Recent Statistics Canada estimates suggest spending erosion. Driven by declining investment in oil and gas extraction and software, Canadian business R&D is projected to decline by 2.8% per year between 2014 to 2017. While it is incontrovertible that Canadian industrial R&D spending is declining and is concentrated in industries that are intrinsically less R&D intensive than others, the Panel notes that labels of strength or weakness may be misleading. They miss the details of the technological, economic, and social context that influences industrial R&D activity. This underscores the importance of understanding the particular dynamics within industries.

6) The barriers between innovation and wealth creation in Canada are more significant than those between R&D and innovation. The result is a deficit of technology start-ups growing to scale in Canada, and a loss of economic benefits.

Canada's innovation performance reflects complex dynamics linking basic research, technological development, and commercialization. It would be wrong to conclude that, based on a relative lack of business R&D spending and a poor record of productivity growth, Canada suffers from a deficit of innovation or from entrenched barriers to research commercialization more severe than those faced by other countries. A full review of the evidence suggests a more complex picture.

While business R&D spending has continued to falter in Canada, aggregate data from Statistics Canada and the OECD — often two or more years out of date — may exaggerate the challenges faced by Canada's technology firms today. Global trends such as the advent of smart manufacturing, 3D printing, increasing adoption of AI in many industries, and the proliferation of software as a service (SaaS) business models have led to a heightened focus on technology services and design. In the Panel's opinion, this plays to Canadian strengths and has contributed to the emergence of robust ICT service industries and a plethora of new software start-ups. Optimism is growing in the tech sector in Canada. Many stakeholders believe that a critical mass has been reached in the Toronto–Waterloo corridor, Vancouver, Ottawa, and Montréal, fuelling an acceleration in growth, an expansion of financing opportunities, and new possibilities for collaboration. There has also been a resurgence in foreign MNEs interested in basing R&D centres in Canada to take advantage of Canada's research talent, sometimes related to key technology platforms such as AI.

With abundant research talent and low barriers to business creation, Canada has also established itself as a favourable environment for technological start-ups. Recent international assessments rank Canada highly when it comes to entrepreneurial activity. The Canadian VC environment, though not on a par with that of Silicon Valley, has dramatically improved and is now highly competitive internationally. The shift towards smart factories and SaaS is favourable to Canada's national competitiveness given the strength of its technical personnel and capacity in design research. This Panel has found little evidence to suggest that systemic barriers are impeding the translation of Canada's research strengths into innovation.

Barriers impeding the translation of innovation into wealth creation are more significant, however, especially in scaling up successful firms. Canada's promising start-ups are often acquired and developed in other countries, leading to a loss of economic and commercial benefits for Canada. Many factors contribute to this, including the larger size of the U.S. market and China's growing interest in Canadian commercial activities. Universities and governments could do more to help Canadian firms access patents held by universities and develop advanced IP management skills, thereby enabling firms to compete more effectively in a global commercial environment where IP strategy is critical. Recent survey evidence from Canadian firms and tech stakeholders suggests that a lack of managerial talent and experience in growing technology firms to scale is a critical impediment in Canada. The failure to grow larger R&D firms domestically contributes to a lack of larger R&D performers and anchor companies, diminishing both the absorptive capacity for research in industry and the level of private-sector investment in R&D. Moreover, the failure to grow successful start-ups in Canada becomes self-perpetuating. The deficit of domestic managerial experience with scaling up rapidly growing tech companies is a key reason for firms to seek foreign acquirers, thereby diminishing opportunities to develop the needed expertise in Canada.

7) Data limitations continue to constrain the assessment of R&D activity and excellence in Canada, particularly in industrial R&D and in the social sciences, arts, and humanities.

Limitations and weaknesses in the data are noted throughout this report. Some of these limitations are being addressed through changes in data collection methodologies, such as those undertaken by Statistics Canada for its collection of industrial R&D data. Others are inherent characteristics of the data sources. Bibliometrics, though useful in providing a national snapshot of research trends, can only provide a partial account of research impact, and is of limited applicability to a number of research fields. Similarly, patents are only one measure for assessing trends in technology development. The tracking of other components of IP, such as the use of domains, copyright, and design, could be improved. Other indicators and methodologies are feasible; however, with few exceptions, data are not collected widely enough to support international or cross-field comparisons. The CCA survey of top-cited researchers compensates for some of these metrics' weaknesses in assessing research, but is subject to its own limitations and biases. Most indicators are also retrospective in nature (R&D funding is the main exception), illuminating impacts and trends years later. Policy-makers could benefit from better forward-looking measures that can identify emerging research trends as they occur. In the absence of such measures, expert insights continue to be a primary source of evidence about which research areas are emerging as potential areas of growth.

Two weaknesses in the quality of available evidence are especially limiting. First, the data on industrial R&D activity in Canada continue to suffer from several deficiencies. Recent changes introduced by Statistics Canada have improved the timeliness and transparency of this data. However, for international comparisons of industrial R&D intensity by sector and industry, long time lags persist. In an environment where technological advances and changes in market conditions happen rapidly, reducing these lags in the OECD data would improve its usefulness for policy-makers. The assignment of R&D to industry according to NAICS (or ISIC) codes also continues to be problematic, sometimes obscuring important trends. Statistics Canada has partially addressed this by providing more granular data for industries such as Wholesale Trade and Information and Cultural Industries, but it remains a challenge — especially in the services sector where the data fail to illuminate the nature of much of the R&D being conducted. Improving this categorization is challenging given the need for international comparability. However, statistical agencies could explore adding supplementary categorizations based on the technological domain, using terms more in line with those used by industries themselves (e.g., software as a service, biotechnology, clean energy). Finally, there is a lack of internationally comparable metrics on industrial R&D outputs and impacts, aside from those based on patents. More work could be done to develop survey instruments that collect data on the perceptions of international business leaders and corporate R&D managers of the relative strengths of national R&D efforts across a variety of domains.

Second, assessing research performance in the humanities, social sciences, and arts continues to be problematic. While research output and impact can be gauged in these disciplines through metrics based on journal articles and other indexed publications, this provides, at best, an incomplete and uneven picture of research contributions among these fields. The continued expansion of bibliometric databases (including ever-growing coverage of academic books) and methodological improvements (including more use of web-based metrics such as paper views/downloads and social media references) will support ongoing, incremental improvements in the availability and accuracy of data. These improvements, however, will not address fundamental limitations, such as the challenge of assessing research fields with outputs and impacts that are difficult, if not impossible, to quantify. Future assessments may consequently benefit from more substantive integration of methods based on expert review, capable of factoring in different types of research outputs (e.g., non-indexed books) and impacts (e.g., contributions to communities or impacts on public policy). Researchers, analysts, and policy-makers should continue supporting the development of better assessment strategies. The Panel is confident that contributions from the humanities, arts, and social sciences are of equal importance to national prosperity (social and cultural, as well as economic) as those from the more readily measurable S&T disciplines and industrial activities. It is vital that such contributions are better measured and assessed to enable strategic policy development.

FINAL REFLECTIONS

Canada's largely undiminished capacity for high-quality research and extensive pools of research talent are a legacy of past investments. Canada remains home to world-leading researchers, facilities, and programs, and the international community continues to hold their accomplishments and importance in high esteem. A broad base of research talent, a stable macroeconomic context, a diverse and welcoming social environment, and a history of seminal R&D contributions also make Canada an attractive location for researchers, entrepreneurs, and innovative firms. These are Canada's most important R&D strengths and they apply across all domains of research. Together, they could serve as the foundation for a future where Canada continues to support world-leading research and counts among the most innovative and productive economies.

Currently, however, that future seems uncertain. Declining levels of private and public R&D investment threaten to erode Canada's research capacity over time. The loss of innovative, start-ups to foreign buyers, and the inability to grow a sufficient number of start-ups to scale, means that Canadians have not fully captured the economic benefits stemming from Canadian research advances. Addressing these dual challenges — declining R&D investment on the one hand and a deficit of domestic tech companies growing to scale on the other — requires concerted effort from all quarters, including governments, post-secondary institutions, and industry. It may also require new policy approaches for addressing what appear to be systemic, entrenched features of Canada's economic landscape, and for overcoming the inertia inherent in current, anemic patterns of institutional support for R&D. Success in these efforts is not assured, but, the Panel believes that it is entirely possible given Canada's persistent base of cross-cutting R&D strengths. The gains from an improved state of R&D in the future would make it well worth the effort.

References

References

Accel-Rx. (2017). Our Approach. Retrieved December 2017, from https://www.accel-rx.com/about/#approach.

Adner, R. (2006). Match your innovation strategy to your innovation ecosystem. *Harvard Business Review, 84*(4), 98.

Advisory Panel for the Review of Federal Support for Fundamental Science. (2017). *Investing in Canada's Future: Strengthening the Foundations of Canadian Research.* Ottawa (ON): Advisory Panel for the Review of Federal Support for Fundamental Science.

AI-EES (Alberta Innovates - Energy and Environment Solutions). (2014). *Turning Ideas into Action: 2011-12 Report on Outcomes.* Edmonton (AB): AI-EES.

AIAC (Aerospace Industries Association of Canada). (2016). *Aerospace Innovation White Paper: Innovation Agenda Submission.* Ottawa (ON): AIAC.

Aluminium Research Centre. (2017). Université du Québec à Chicoutimi. Retrieved December 2017, from https://www.regal-aluminium.ca/en/about/institutions-en/uqac/.

Archambault, E., Vignola-Gagne, E., Cote, G., Larivière, V., & Gingras, Y. (2006). Benchmarking scientific output in the social sciences and humanities: The limits of existing databases. *Scientometrics, 68*(3), 329-342.

Arundel, A. & Bordoy, C. (2008). *Developing Internationally Comparable Indicators for the Commercialization of Publicly-Funded Research.* Maastricht, Netherlands: United Nations University - Maastricht Economic and Social Research and Training Centre on Innovation and Technology.

AUTM (Association of University Technology Managers). (2015a). Statistics Access for Technology Transfer (STATT) Database. Retrieved July 2017, from https://www.autm.net/resources-surveys/research-reports-databases/statt-database-(1)/.

AUTM (Association of University Technology Managers). (2015b). *Highlights of AUTM's Canadian Licensing Activity Survey FY2015.* Washington (DC): AUTM.

Baldwin, J. R. & Gu, W. (2009). *Productivity Performance in Canada, 1961 to 2008: An Update on Long-term Trends.* Ottawa (ON): Statistics Canada.

Bawa, K. (2017). After Failing to Commercialize, Universities Learn to Set Ideas Free. In *New Thinking on Innovation.* Waterloo (ON): Centre for International Governance Innovation.

BDC (Business Development Bank of Canada). (2013). *What's Happened to Canada's Mid-Sized Firms?* Ottawa (ON): BDC.

BDC (Business Development Bank of Canada). (2015). *High-Impact Firms: Accelerating Canadian Competitiveness.* Ottawa (ON): BDC.

Beaudry, C. & Schiffauerova, A. (2011). Is Canadian intellectual property leaving Canada? A study of nanotechnology patenting. *The Journal of Technology Transfer, 36*(6), 665-679.

Beckstead, D., Brown, W. M., Guo, Y., & Newbold, K. B. (2010). *Cities and Growth: Earnings Levels Across Urban and Rural Areas: The Role of Human Capital.* Ottawa (ON): Statistics Canada.

Behrens, K., Duranton, G., & Robert-Nicoud, F. (2014). Productive cities: Agglomeration, selection and sorting. *Journal of Political Economy, 122*(3), 507-553.

Bérubé, C. & Therrien, P. (2016). *Direct and Indirect Support to Business R&D.* Ottawa (ON): Innovation, Science, and Economic Development Canada.

Bettencourt, L., Lobo, J., Helbing, D., Kühnert, C., & West, G. (2007). Growth, innovation, scaling, and the pace of life in cities. *Proceedings of the National Academy of Sciences, 104*(17), 7301-7306.

Bettencourt, L., Lobo, J., Strumsky, D., & West, G. (2010). Urban scaling and its deviations: Revealing the structure of wealth, innovation and crime across cities. *PLoS ONE, 5*(11), e13541.

Bibbee, A. (2012). *Unleashing Business Innovation in Canada.* Paris, France: OECD Economics Department Working Papers.

Birch, D. L. (1979). *The Job Generation Process: Final Report to Economic Development Administration.* Cambridge (MA): MIT Program on Neighborhood and Regional Change.

Blit, J. (2017). Toward an Optimal Patent Regime for Canada. In *New Thinking on Innovation.* Waterloo (ON): Centre for International Governance Innovation.

Bostrom, N. (2014). *Superintelligence: Paths, Dangers, Strategies.* Oxford, United Kingdom: Oxford University Press.

Bravo-Biosca, A., Criscuolo, C., & Menon, C. (2014). What Drives the Dynamics of Business Growth? London, United Kingdom: Nesta Working Paper.

Breznitz, D., Breznitz, S., & Wolfe, D. A. (2015). *Current State of the Financial Technology Innovation Ecosystem in the Toronto Region.* Toronto (ON): Innovation Policy Lab, Munk School of Global Affairs, University of Toronto.

Brickley, P. (2011, July 11). Nortel $4.5-Billion Patent Sale to Apple, Microsoft, Others Approved, *The Wall Street Journal.*

Britton, J. N. H. & Gilmour, J. M. (1978). *The Weakest Link: A Technological Perspective on Canadian Industrial Underdevelopment.* Ottawa (ON): Science Council of Canada.

Burt, M. (2016). *An Engine for Growth: 2016 Report Card on Canada and Toronto's Financial Services Sector.* Ottawa (ON): The Conference Board of Canada.

Bush, V. (1945). *Science, the Endless Frontier: A Report to the President.* Washington (DC): United States Government Printing Office.

CAPP (Canadian Association of Petroleum Producers). (2017). *Crude Oil Forecast, Markets and Transportation*. Calgary (AB): CAPP.

CBOC (The Conference Board of Canada). (2015). How Canada Performs: Innovation. Retrieved March 2017, from http://www.conferenceboard.ca/hcp/provincial/innovation.aspx.

CCA (Council of Canadian Academies). (2006). *The State of Science and Technology in Canada, 2006*. Ottawa (ON): The Expert Panel on the State of Science and Technology in Canada, CCA.

CCA (Council of Canadian Academies). (2009). *Innovation and Business Strategy: Why Canada Falls Short*. Ottawa (ON): The Expert Panel on Business Innovation, CCA.

CCA (Council of Canadian Academies). (2012a). *The State of Science and Technology in Canada, 2012*. Ottawa (ON): The Expert Panel on the State of Science and Technology in Canada, CCA.

CCA (Council of Canadian Academies). (2012b). *Informing Research Choices: Indicators and Judgment*. Ottawa (ON): The Expert Panel on Science Performance and Research Funding, CCA.

CCA (Council of Canadian Academies). (2013a). *Innovation Impacts: Measurement and Assessment*. Ottawa (ON): The Expert Panel on the Socio-economic Impacts of Innovation Investments, CCA.

CCA (Council of Canadian Academies). (2013b). *The State of Industrial R&D in Canada*. Ottawa (ON): The Expert Panel on the State of Industrial R&D in Canada, CCA.

CCA (Council of Canadian Academies). (2013c). *Paradox Lost: Explaining Canada's Research Strength and Innovation Weakness*. Ottawa (ON): Advisory Group, CCA.

CCA (Council of Canadian Academies). (2015a). *Some Assembly Required: STEM Skills and Canada's Economic Productivity*. Ottawa (ON): The Expert Panel on STEM Skills for the Future, CCA.

CCA (Council of Canadian Academies). (2015b). *Technological Prospects for Reducing the Environmental Footprint of Canadian Oil Sands*. Ottawa (ON): The Expert Panel on the Potential for New and Emerging Technologies to Reduce the Environmental Impacts of Oil Sands Development, CCA.

CCA (Council of Canadian Academies). (2016). *Preliminary Data Update on Canadian Research Performance and International Reputation*. Ottawa (ON): The Expert Panel on the State of S&T and IR&D in Canada, CCA.

CDL (Creative Destruction Lab). (2017). Build Something Massive. Retrieved July 2017, from https://www.creativedestructionlab.com/.

CDRD (The Centre for Drug Research and Development). (2017). Outcomes & Impacts. Retrieved July 2017, from http://www.cdrd.ca/outcomes-impact/.

CERN (European Organization for Nuclear Research). (2015). CERN Turns 60, Celebrates Peaceful Collaboration for Science. Retrieved June 2017, from https://home.cern/about/updates/2014/09/cern-turns-60-celebrates-peaceful-collaboration-science.

Cervantes, M. (n.d.). Academic Patenting: How Universities and Public Research Organizations Are Using their Intellectual Property to Boost Research and Spur Innovative Start-Ups. Retrieved July 2017, from http://www.wipo.int/sme/en/documents/academic_patenting.html.

CGE (Canadian Government Executive). (2016). Ontario, Huawei - Canada Partner in $300M 5G Project. Retrieved June 2017, from http://canadiangovernmentexecutive.ca/ontario-huawei-canada-partner-in-300m-5g-project/.

Chiose, S. A. (2017, May 14). Canadian Universities See Surge of International Students, *The Globe and Mail*.

CIFAR (Canadian Institute for Advanced Research). (2016). CIFAR's Submission to the Expert Panel on Canada's Fundamental Science Review. Retrieved April 2017, from https://www.cifar.ca/wp-content/uploads/ReviewFundamentalScience-CIFARSubmission.pdf.

Coad, A., Daunfeldt, S.-O., Hölzl, W., Johansson, D., & Nightingale, P. (2014). High-growth firms: Introduction to the special section. *Industrial and Corporate Change, 23*(1), 91-112.

Cohen, W. (2010). Fifty Years of Empirical Studies of Innovative Activity and Performance. In B. Hall & N. Rosenberg (Eds.), *Handbook of the Economics of Innovation: Volume 1*. Amsterdam, Netherlands: Elsevier.

COSIA (Canada's Oil Sands Innovation Alliance). (2016). About COSIA. Retrieved April 2017, from http://www.cosia.ca/about-cosia.

Côté, S. & Rosa, J. M. (2017). *Comparing Different Measures of High-Growth Enterprises: A Canadian Case Study*. Ottawa (ON): Innovation, Science and Economic Development Canada.

CQDM (Centre québécois de développement du médicament). (2016). *Filling the Gap: Annual Report 2016*. Montréal (QC): CQDM.

CQDM (Centre québécois de développement du médicament). (2017a). Facts and Figures. Retrieved June 2017, from https://www.cqdm.org/en/about-us/facts-and-figures.php.

CQDM (Centre québécois de développement du médicament). (2017b). Mission and Business Model. Retrieved June 2017, from https://www.cqdm.org/en/about-us/mission-and-business-model.php.

Creso, S. (2016, August 9). Canada’s R&D Tax Credit Doesn’t Pass the Test for Evidence-based Policy, *The Globe and Mail*.

CRIAQ (Consortium de recherche et d'innovation en aérospatiale au Québec). (2015). *Propelling Ourselves Together*. Montréal (QC): CRIAQ.

CVCA (Canadian Venture Capital & Private Equity Association). (2017). Three Years into VCAP and Program Still Propelling Canada's Innovation Ecosystem. Retrieved September 2017, from http://news.cvca.ca/three-years-into-vcap-and-program-still-propelling-canadas-innovation-ecosystem/2017/01/23/.

Daunfeldt, S.-O., Johansson, D., & Halvarsson, D. (2015). Using the eurostat-OECD definition of high-growth firms: A cautionary note. *Journal of Entrepreneurship and Public Policy, 4*(1), 50-56.

Davis, D. & Dingel, J. (2017). *The Comparative Advantage of Cities.* Cambridge (MA): National Bureau of Economic Research.

DEEP Centre (Centre for Digital Entrpreneurship + Economic Performance). (2015). *Accelerating Canada's Start-Up Ecosystem: A Review of Canadian Business Accelerators and Business Incubators.* Waterloo (ON): DEEP Centre.

Delgado, M., Porter, M. E., & Stern, S. (2014). Clusters, convergence, and economic performance. *Research Policy, 43*(10), 1785-1799.

Deloitte. (2012). *The Future of Productivity: Clear Choices for a Competitive Canada.* Ottawa (ON): Deloitte.

Deloitte. (2016). *Global Trends: Government Incentives for Innovation and Investment.* Ottawa (ON): Deloitte.

Deloitte. (2017). The Future Belongs to the Bold. Retrieved November 2017, from https://www2.deloitte.com/ca/en/pages/insights-and-issues/articles/the-future-belongs-to-the-bold-new.html.

Diamond, J. (1997). *Guns, Germs, and Steel: The Fates of Human Societies.* New York (NY): W. W. Norton & Company.

Dixon, J. & Rollin, A. (2014). *The Distribution of Employment Growth Rates in Canada: The Role of High-Growth and Rapidly Shrinking Firms.* Ottawa (ON): Statistics Canada.

Edge, J. & Munro, D. (2015). *Inside and Outside the Academy: Valuing and Preparing PhDs for Careers.* Ottawa (ON): The Conference Board of Canada.

Emerson, D., Roy, J., Pupatello, S., & Quick, J. (2012). *Volume 1: Beyond the Horizon: Canada's Interests and Future in Aerospace.* Ottawa (ON): Public Works and Government Services Canada.

Engardio, P., Einhorn, B., Kripalani, M., Reinhardt, A., Nussbaum, B., & Burrows, P. (2005). Outsourcing Innovation. In D. Mayle (Ed.), *Managing Innovation and Change.* Thousand Oaks (CA): Sage Publications Ltd.

ERA (Emissions Reduction Alberta). (2017). News. Retrieved April 2017, from http://www.eralberta.ca/#news.

Erlick, N. (2017, July 27). AI Pioneer Will Advise Chatbot Startup that Provides Free Legal Advice to Immigrants, *The Verge.*

ESDC (Employment and Social Development Canada). (2017). Social Innovation and Social Finance Strategy Co-Creation Steering Group. Retrieved September 2017, from https://www.canada.ca/en/employment-social-development/programs/social-innovation-social-finance/steering-group.html.

Expert Panel on Commercialization. (2006). *People and Excellence: The Heart of Successful Commercialization; Talent, Research, Capital. Volume 1: Final Report of the Expert Panel on Commercialization.* Ottawa (ON): Industry Canada.

Galindo-Rueda, F. & Verger, F. (2016). *OECD Taxonomy of Economic Activities Based on R&D Intensity.* Paris, France: OECD Publishing.

Galushko, V. & Sagynbekov, K. (2014). Commercialization of university research in Canada: What can we do better? *International Journal of Business Administration, 5*(5), 1-13.

GC (Government of Canada). (2014). *Seizing Canada's Moment: Moving Forward in Science, Technology and Innovation 2014.* Ottawa (ON): Industry Canada.

GC (Government of Canada). (2017). *Building a Strong Middle Class #Budget2017.* Ottawa (ON): Finance Canada.

GEDI (Global Entrepreneurship and Development Institute). (2017). Global Entrepreneurship Index. Retrieved April 2017, from https://thegedi.org/global-entrepreneurship-and-development-index/.

Genome Canada. (2017). New Support for Structural Genomics Consortium and Open Science. Retrieved January 2018, from https://www.genomecanada.ca/en/news-and-events/news-releases/new-support-structural-genomics-consortium-and-open-science.

Giannone, E. (2017). *Skilled-Biased Technical Change and Regional Convergence.* Chicago (IL): University of Chicago.

Glaeser, E. & Resseger, M. (2010). The complementarity between cities and skills. *Journal of Regional Science, 50*(1), 221-244.

Glaeser, E. (2011). Cities, productivity, and quality of life. *Science, 333*(6042), 592-594.

Glaeser, E. (Ed.). (2010). *Agglomeration Economics.* Chicago (IL): University of Chicago.

GM Canada (General Motors Canada). (2016). General Motors Announces Expansion of Connected and Autonomous Vehicle Engineering and Software Development Work in Canada. Retrieved January 2018, from http://media.gm.ca/media/ca/en/gm/home.detail.html/content/Pages/news/ca/en/2016/Jun/0610_EngCentre.html.

Goldenberg, M., Kamoji, W., Orton, L., & Williamson, M. (2009). *Social Innovation in Canada: An Update.* Ottawa (ON): Canadian Policy Research Networks.

Goracinova, E., Warrian, P., & Wolfe, D. A. (2017). Challenges of coordination: Automotive innovation in the Ontario supply chain in comparative context. *Canadian Public Policy, 43*(S1), S90-S102.

Greenspon, J. & Rodigues, E. (2017). *Are Trends in Patenting Reflective of Innovative Activity in Canada?* Ottawa (ON): Centre for the Study of Living Standards.

Gupta, K. (2012). *The Issue: Building Stronger Tech Companies in Canada.* Ottawa (ON): Information Technology Association of Canada.

Hall, B. H., Mairesse, J., & Mohnen, P. (2010). Measuring the Returns to R&D. In B. H. Hall & N. Rosenberg (Eds.), *Handbook of Economics of Innovation: Volume 2.* Amsterdam, Netherlands: Elsevier.

Hathaway, I. & Litan, R. (2014). *Declining Business Dynamism in the United States: A Look at States and Metros.* Washington (DC): The Brookings Institution.

Hepburn, N. & Wolfe, D. A. (2015). Commercialization and Technology Transfer Policies and Intellectual Property Regimes in Canada. In S. Breznitz & H. Etzkowitz (Eds.), *University Technology Transfer: The Globalization of Academic Innovation.* New York (NY): Routledge.

Hermann, M., Pentek, T., & Otto, B. (2016). *Design Principles for Industrie 4.0 Scenarios.* Paper presented at 49th Hawaii International Conference on System Sciences, Kauai (HI).

Ho, S. (2017). Canadian FinTechs Shine as Investments Near Record. Retrieved December 2017, from https://www.reuters.com/article/us-canada-fintech/canadian-fintechs-shine-as-investments-near-record-idUSKBN14N1N5.

Hvistendahl, M. (2013). China's publication bazaar. *Science, 342*(6162), 1035-1039.

IMF (International Monetary Fund). (2016). IMF Sees Subdued Global Growth, Warns Economic Stagnation Could Fuel Protectionist Calls. Retrieved October 2017, from http://www.imf.org/en/News/Articles/2016/10/03/AM2016-NA100416-WEO.

ISED (Innovation, Science and Economic Development Canada). (2016). *Key Small Business Statistics.* Ottawa (ON): ISED.

ISED & AIAC (Innovation, Science and Economic Development Canada and Aerospace Industries Association of Canada). (2016). *State of Canada's Aerospace Industry 2016 Report.* Ottawa (ON): ISED.

Jackson, D. J. (2011). *What Is an Innovation Ecosystem?* Arlington (VA): National Science Foundation.

Jaffe, A. & Lerner, J. (2006). *Innovation and Its Discontents: How Our Broken Patent System Is Endangering Innovation and Progress, and What to Do About It.* Princeton (NJ): Princeton University Press.

Jones, C. (2016). The Facts of Economic Growth. In J. B. Taylor & H. Uhlig (Eds.), *Handbook of Macroeconomics*: Volume 2A. Amsterdam, Netherlands: Elsevier.

Kenney, M. & Patton, D. (2011). Does inventor ownership encourage university research-derived entrepreneurship? A six university comparison. *Research Policy, 40*(8), 1100-1112.

Kolm, J. (2017). Big Brands Sign on with Government-Backed AI Institute. Retrieved December 2017, from http://strategyonline.ca/2017/03/30/big-brands-sign-on-with-government-backed-ai-institute/.

KPMG Enterprise & Ivey Business School. (2015). *An Ice Ceiling: Overcoming the Growth Challenges Faced by Canada's Mid-Sized Companies*. Ottawa (ON): KPMG Enterprise.

KPMG Enterprise. (2016). *Make It Happen: Canadian Manufacturing Outlook 2016*. Toronto (ON): KPMG Enterprise.

Krugman, P. (1991). Increasing returns and economic geography. *Journal of Political Economy, 99*(3), 483-499.

Langford, C. H., Josty, P., & Saunders, C. (2015). *2015 GEM Canada National Report*. London, United Kingdom: Global Entrepreneurship Monitor.

Lazaridis Institute. (2016). *Scaling Success: Tackling the Management Gap in Canada's Technology Sector*. Waterloo (ON): Lazardis Institute, Wilfred Laurier University.

Lonmo, C. (2007). *Innovators, Non-innovators and Venture Firms: What Is the Nature of Firms in Research and Development Services Industries?* Ottawa (ON): Statistics Canada.

Mairesse, J. & Mohnen, P. (2010). Using Innovation Surveys for Econometric Analysis. In B. H. Hall & N. Rosenberg (Eds.), *Handbook of the Economics of Innovation: Volume 2*. Amsterdam, Netherlands: Elsevier.

MaRS. (2017). Health. Retrieved December 2017, from https://www.marsdd.com/our-sectors/health/.

Martin, H., Wright, R., & Cowan, A. (2014). *Human Resources Trends and Metrics: HR Measurement Benchmarking, Third Edition*. Ottawa (ON): The Conference Board of Canada.

Mazurkewich, K. (2011). *Rights and Rents: Why Canada Must Harness its Intellectual Property Resources*. Toronto (ON): Canadian International Council.

McKinsey & Company. (2016). *Tech North: Building Canada's First Technology Supercluster*. Toronto (ON): McKinsey & Company.

Mitacs. (2016). *2016 Year in review*. Montréal (QC): Mitacs.

Moed, H. F. (2005). *Citation Analysis in Research Evaluation*. Dordrecht, Netherlands: Springer.

Moffatt, M. (2016). *How to Innovate FinTech in Canada*. Ottawa (ON): Canada 2020.

Moretti, E. (2012). *The New Geography of Jobs*. New York (NY): Houghton Mifflin Harcourt.

Mowery, D., Nelson, R., Sampat, B., & Ziedonis, A. (2004). *Ivory Tower and Industrial Innovation: University-Industry Technology Transfer Before and After the Bayh-Dole Act*. Stanford (CA): Stanford University Press.

Munos, B. (2015). How to handle an industry in disruption: Intervene or laissez-faire? *Science Translational Medicine, 7*(286), 1-4.

Munro, D. (2009). *Report Card on Management, Business, and Finance Education in Canada: Are Graduates Ready for Business?* Ottawa (ON): The Conference Board of Canada.

Munro, D. (2015). *Canada's Venture Capital Opportunity*. Ottawa (ON): The Conference Board of Canada.

Murphy, J. (2011). *Research and Development Summary Report*. Paper presented at 26th Voorburg Group Meeting, Newport, United Kingdom.

NASEM (National Academies of Sciences, Engineering, and Medicine). (2017). *Advancing Concepts and Models for Measuring Innovation: Proceedings of a Workshop*. Washington (DC): National Academies Press.

NEOMED Institute. (2012). Création de l'Institut NEOMED – un renouveau pour la recherche biopharmaceutique au Québec. Retrieved December 2017, from http://neomed.ca/en/2012/11/23/astrazeneca-canada-and-pfizer-canada-join-forces-with-the-government-of-quebec-to-establish-a-new-rd-model-in-the-biopharmaceutical-industry/.

NEOMED Institute. (2015). NEOMED Creates a New Biologics and Vaccine Centre of Excellence. Retrieved December 2017, from http://neomed.ca/en/2015/02/05/neomed-creates-a-new-biologics-and-vaccine-centre-of-excellence/.

NEOMED Institute. (2017a). About: Mission & Business Model. Retrieved June 2017, from http://neomed.ca/en/about/mission-business-model/.

NEOMED Institute. (2017b). About: Facts & Highlights. Retrieved June 2017 from http://neomed.ca/en/about/facts-highlights/.

NESTA (National Endowment for Science Technology and the Arts). (2009). *The Vital 6 Per Cent: How High-Growth Innovative Businesses Generate Prosperity and Jobs*. London, United Kingdom: NESTA.

neuro (Montreal Neurological Institute and Hospital). (n.d.). Open Science - Science Reimagined. Retrieved January 2018, from https://www.mcgill.ca/neuro/open-science-0.

Nicholls, A. & Murdock, A. (2012). The Nature of Social Innovation. In A. Nicholls & A. Murdock (Eds.), *Social Innovation*. London, United Kindom: Palgrave Macmillan.

Nicholson, P. (2016). Canada's low-innovation equilibrium: Why it has been sustained and how it will be disrupted. *Canadian Public Policy, 42*(s1), S39-S45.

Niosi, J. (2008). Technology, development and innovation systems: An introduction. *The Journal of Development Studies, 44*(5), 613-621.

Niu, J., Tang, W., Xu, F., Zhou, X., & Song, Y. (2016). Global research on artificial intelligence from 1990–2014: Spatially-explicit bibliometric analysis. *ISPRS International Journal of Geo-Information, 5*(66), 1-19.

NRC (National Research Council). (2014). *Capturing Change in Science, Technology, and Innovation: Improving Indicators to Inform Policy*. Washington (DC): Panel on Developing Science, Technology, and Innovation Indicators for the Future.

NSB (National Science Board). (2016). *Science and Engineering Indicators 2016*. Arlington (VA): NSB.

NSERC (Natural Sciences and Engineering Research Council of Canada). (nd-a). NSERC Partner Final Report. Retrieved December 2017, from http://nserc-sshrc.fluidsurveys.com/share/371c1998e8d00f4623d3/.

NSERC (Natural Sciences and Engineering Research Council). (nd-b). NSERC Drives Innovation. Retrieved December 2017, from http://www.nserc-crsng.gc.ca/_doc/Innovation-Factsheet-EN.pdf.

NSERC (Natural Sciences and Engineering Research Council of Canada). (2017a). NSERC's Awards Database. Retrieved December 2017, from http://www.nserc-crsng.gc.ca/ase-oro/Results-Resultats_eng.asp.

NSERC (Natural Sciences and Engineering Research Council of Canada). (2017b). Chairholder Profile. Retrieved December 2017, from http://www.nserc-crsng.gc.ca/Chairholders-TitulairesDeChaire/Chairholder-Titulaire_eng.asp?pid=518.

OEC (The Observatory of Economic Complexity). (n.d.). Canada. Retrieved January 2018, from https://atlas.media.mit.edu/en/profile/country/can/.

OECD (Organisation for Economic Co-operation and Development). (2009). *Innovation in Firms: A Microeconomic Perspective*. Paris, France: OECD Publishing.

OECD (Organisation for Economic Co-operation and Development). (2011a). *Entrepreneurship at a Glance 2011*. Paris, France: OECD Publishing.

OECD (Organisation for Economic Co-operation and Development). (2011b). *Skills for Innovation and Research*. Paris, France: OECD Publishing.

OECD (Organisation for Economic Co-operation and Development). (2015a). *Science, Technology, and Industry Scoreboard 2015*. Paris, France: OECD Publishing.

OECD (Organisation for Economic Co-operation and Development). (2015b). *Frascati Manual 2015: Guidelines for Collecting and Reporting Data on Research and Experimental Development*. Paris, France: OECD Publishing.

OECD (Organisation for Economic Co-operation and Development). (2015c). *Entrepreneurship at a Glance 2015*. Paris, France: OECD Publishing.

OECD (Organisation for Economic Co-operation and Development). (2016a). Main Science and Technology Indicators. Retrieved January 2018, from http://www.oecd.org/sti/msti.htm.

OECD (Organisation for Economic Co-operation and Development). (2016b). *OECD Economic Surveys: Canada 2016*. Paris, France: OECD Publishing.

OECD (Organisation for Economic Co-operation and Development). (2016c). *Entrepreneurship at a Glance 2016*. Paris, France: OECD Publishing.

OECD (Organisation for Economic Co-operation and Development). (2016d). *R&D Tax Incentive Report: Canada*. Paris, France: OECD Publishing.

OECD (Organisation for Economic Co-operation and Development). (2016e). *Education at a Glance 2016*. Paris, France: OECD Publishing.

OECD (Organisation for Economic Co-operation and Development). (2016f). *OECD Science, Technology and Innovation Outlook 2016*. Paris, France: OECD Publishing.

OECD (Organisation for Economic Co-operation and Development). (2017a). Research and Development Statistics. Retrieved May 2017, from https://stats.oecd.org/.

OECD (Organisation for Economic Co-operation and Development). (2017b). OECD Observatory of Public Sector Innovation. Retrieved September 2017, from https://www.oecd.org/governance/observatory-public-sector-innovation.htm.

OECD (Organisation for Economic Co-operation and Development). (2017c). *OECD Science, Technology and Industry Scoreboard 2017: The Digital Transformation*. Paris, France: OECD Publishing.

OECD (Organisation for Economic Co-operation and Development). (2017d). Productivity and ULC by Main Economic Activity (ISIC Rev.4). Retrieved October 2017, from https://stats.oecd.org/.

OECD/Eurostat (Organisation for Economic Co-operation and Development/Eurostat). (2005). *Oslo Manual: Guidelines for Collecting and Interpreting Innovation Data, 3rd Edition*. Paris, France: OECD Publishing.

Oskamp, S. & Schultz, P. W. (2005). *Attitudes and Opinions*. New York (NY): Psychology Press.

Parsley, C. & Halabisky, D. (2008). *Profile of Growth Firms: A Summary of Industry Canada Research*. Ottawa (ON): Industry Canada.

Phills, J. A., Deiglmeier, K., & Miller, D. T. (2008). Rediscovering social innovation. *Stanford Social Innovation Review, 6*(4), 34-43.

Pinto, D., Goard, C., & Kim, A. (2016). *VC & PE Canadian Market Overview*. Toronto (ON): Canadian Venture Capital and Private Equity Association.

Pohlmann, M. (2014, December 12). Jim Balsillie on commercializing our ideas: 'Where the innovation game is won or lost.', *The Globe and Mail*.

Porter, M. E. (1998). *On Competition*. Boston (MA): Harvard Business School Press.

Porter, M. E., Monitor Group, ontheFRONTIER, & Council on Competitiveness. (2001). *Clusters of Innovation: Regional Foundations of US Competitiveness*. Washington (DC): Council on Competitiveness.

PRI (Policy Research Initiative). (2010). *Social Innovation: What is it? Who Does it?* Ottawa (ON): PRI.

Prince, C., Petijean, C., Benyouci, S., Beaulieu, R., & Noler, D. (2016). CRIAQ and CARIC: An innovation journey - Insights on how to build successful research and development collaborations in aerospace: The case of the Quebec and Canadian ecosystems. *Journal of Innovation Management, 4*(2), 6-15.

PwC (PricewaterhouseCoopers). (2015). *A Nation of Innovators: 2015 Canadian Emerging Technology Companies Survey*. Ottawa (ON): PwC.

Re$earch Infosource Inc. (2016). *Canada's Top 50 Research Universities 2016.* Toronto (ON): Re$earch Infosource Inc.

Re$earch Infosource Inc. (2018). Canada's Top 100 Corporate R&D Spenders. Retrieved January 2018, from https://researchinfosource.com/top100_corp.php.

Richards, E., Lonmo, C., & Gellatly, G. (2017). *Industrial Contributions to Research and Development Spending in Canada.* Ottawa (ON): Statistics Canada.

Rieti, J. (2017, June 6). Toronto Welcoming Artificial Intelligence Company Back from Silicon Valley, *CBC News.*

Rooksby, J. (2013). Innovation and litigation: Tensions between universities and patents and how to fix them. *Yale Journal of Law and Technology, 5*(2), 316-402.

Rousseau, R. (2015). The tip of the Chinese publication iceberg. *ISSI Newsletter, 11*(4), 100-102.

Scott, A. (2008). *Social Economy of the Metropolis: Cognitive-Cultural Capitalism and the Global Resurgence of Cities.* Oxford, United Kingdom: Oxford University Press.

Secretariat to the Review of Federal Support to R&D Expert Panel. (2011). *Assessing the Scientific Research and Experimental Development Tax Credit.* Ottawa (ON): Industry Canada.

Senate Special Committee on Science Policy. (1970). *A Science Policy for Canada.* Ottawa (ON): Senate of Canada.

SGC (Structural Genomics Consortium). (2018). Key Achievements. Retrieved January 2018, from http://www.thesgc.org/about/key_achievements.

Silcoff, S. (2017, March 18). Billion-Dollar Breakout, *The Globe and Mail.*

Simons, P. (2017, December 22). Global Head-Snap: Google's DeepMind Sets Up Shop in Edmonton, *Edmonton Journal.*

Sloan, S. & Dale, J. (2015). *The Importance of C-Suite Talent in Creating High Growth Firms.* Ottawa (ON): Sloan Consultants and Snowy Cloud Inc.

Songsakul, T., Lau, B., & Boothby, D. (2008). *Firm Size and Research and Development Expenditures: A Canada-U.S. Comparison Industry - Working Paper 2008-12.* Ottawa (ON): Industry Canada.

Spencer, G., Vinodrai, T., Gertler, M. S., & Wolfe, D. A. (2010). Do clusters make a difference? Defining and assessing their economic performance. *Regional Studies, 44*(6), 697-715.

Spencer, G. (2014). *Cluster Atlas of Canada*. Toronto (ON): Munk School of Global Affairs.

Startup Genome. (2017). *Global Startup Ecosystem Report 2017*. San Francisco (CA): Startup Genome.

StatCan (Statistics Canada). (2007). *Long-Term Productivity Growth in Canada and the United States*. Ottawa (ON): StatCan.

StatCan (Statistics Canada). (2011). *Population Growth in Canada: From 1851 to 2061*. Ottawa (ON): StatCan.

StatCan (Statistics Canada). (2012a). *CANSIM Table 358-0176. Enterprises Holding or Using Copyrights, by Copyright Size Group and Selected Industry Group, December 2010*. Ottawa (ON): StatCan.

StatCan (Statistics Canada). (2012b). *CANSIM Table 358-0173. Enterprises Holding or Using Issued Patents, by Category of Patent Acquisition and Selected Industry Group, December 2010*. Ottawa (ON): StatCan.

StatCan (Statistics Canada). (2012c). Survey of Intellectual Property Management (SIPM). Retrieved July 2017, from http://www23.statcan.gc.ca/imdb/p2SV.pl?Function=getSurvey&Id=113291.

StatCan (Statistics Canada). (2012d). *CANSIM Table 477-0018. Number and Median Age of Full-Time Teaching Staff at Canadian Universities, by Highest Earned Degree, Staff Functions, Rank, Sex, Canada and Provinces*. Ottawa (ON): StatCan.

StatCan (Statistics Canada). (2012e). *CANSIM Table 358-0182. Enterprises Holding or Using Other Forms of Intellectual Property, by Type and Selected Industry Group, 2010*. Ottawa (ON): StatCan.

StatCan (Statistics Canada). (2013). *CANSIM Table 358-0160. Provincial Distribution of Personnel Engaged in Research and Development, by Performing Sector and Occupational Category*. Ottawa (ON): StatCan.

StatCan (Statistics Canada). (2014a). *CANSIM Table 358-0221. Survey of Innovation and Business Strategy, Innovation, by North American Industry Classification System (NAICS) and Enterprise Size*. Ottawa (ON): StatCan.

StatCan (Statistics Canada). (2014b). *CANSIM Table 358-0268. Survey of Innovation and Business Strategy, Obstacles to Innovation Confronted, by North American Industry Classification System (NAICS) and Enterprise Size, All Surveyed Industries*. Ottawa (ON): StatCan.

StatCan (Statistics Canada). (2015). *Industrial Research and Development: Intentions*. Ottawa (ON): StatCan.

StatCan (Statistics Canada). (2016a). *CANSIM Table 051-0001. Estimates of Population, by Age Group and Sex for July 1, Canada, Provinces and Territories*. Ottawa (ON): StatCan.

StatCan (Statistics Canada). (2016b). *CANSIM Table 477-0032. Postsecondary Graduates, by Student Status, Country of Citizenship and Sex*. Ottawa (ON): StatCan.

StatCan (Statistics Canada). (2016c). Research and Development in Canadian Industry (RDCI). Retrieved July 2017, from http://www23.statcan.gc.ca/imdb-bmdi/document/4201_D6_T9_V1-eng.htm.

StatCan (Statistics Canada). (2016d). *CANSIM Table 384-0038. Gross Domestic Product, Expenditure-Based, Provincial and Territorial*. Ottawa (ON): StatCan.

StatCan (Statistics Canada). (2016e). *North American Industry Classification System (NAICS) Canada, 2017 Version 1.0*. Ottawa (ON): StatCan.

StatCan (Statistics Canada). (2017a). *CANSIM Table 358-0211. Business Enterprise Current Intramural Research and Development Expenditures as a Percentage of Performing Research and Development Company Revenues, by Country of Control and North American Industry Classification System (NAICS)*. Ottawa (ON): StatCan.

StatCan (Statistics Canada). (2017b). Survey of Innovation and Business Strategy. Retrieved September 2017, from http://www23.statcan.gc.ca/imdb/p2SV.pl?Function=getSurvey&SDDS=5171.

StatCan (Statistics Canada). (2017c). *CANSIM Table 358-0510. Business Enterprise In-House Research and Development Expenditures, by Industry Group Based on the North American Industry Classification System (NAICS), Country of Control and Expenditure Types*. Ottawa (ON): StatCan.

StatCan (Statistics Canada). (2017d). *CANSIM Table 358-0205. Business Enterprise Intramural Research and Development Expenditures, by Country of Control and North American Industry Classification System (NAICS)*. Ottawa (ON): StatCan.

StatCan (Statistics Canada). (2017e). *CANSIM Table 477-0036. Postsecondary Graduates, by Program Type, Credential Type, Age Groups and Sex*. Ottawa (ON): StatCan.

StatCan (Statistics Canada). (2017f). *CANSIM Table 358-0206. Business Enterprise Extramural Payments for Research and Development, by Location of Recipient and North American Industry Classification System (NAICS)*. Ottawa (ON): StatCan.

StatCan (Statistics Canada). (2017g). Gross Domestic Expenditures on Research and Development (GERD) as a Percentage of Gross Domestic Product. Retrieved October 2017, from http://www.statcan.gc.ca/tables-tableaux/sum-som/l01/cst01/scte03-eng.htm.

StatCan (Statistics Canada). (2017h). *CANSIM Table 358-0001. Gross Domestic Expenditures on Research and Development, by Science Type and by Funder and Performer Sector*. Ottawa (ON): StatCan.

StatCan (Statistics Canada). (2017i). *CANSIM Table 358-0141. Business Enterprise Extramural Payments for Research and Development, by Location and Sector of Recipients*. Ottawa (ON): StatCan.

StatCan (Statistics Canada). (2017j). *CANSIM Table 358-0140. Business Enterprise Research and Development (R&D) Characteristics, by Field of Science or Technology and North American Industry Classification System (NAICS)*. Ottawa (ON): StatCan.

StatCan (Statistics Canada). (2017k). *CANSIM Table 358-0209. Business Enterprise Intramural Research and Development Expenditures, by Performing Company Revenue Size*. Ottawa (ON): StatCan.

StatCan (Statistics Canada). (2017l). *CANSIM Table 358-0208. Business Enterprise Intramural Research and Development Expenditures, by Performing Company Employment Size*. Ottawa (ON): StatCan.

StatCan (Statistics Canada). (2017m). *CANSIM Table 358-0159. Personnel Engaged in Research and Development, by Performing Sector, Occupational Category and Type of Science*. Ottawa (ON): StatCan.

StatCan (Statistics Canada). (2017n). Payroll Employment, by Industry. Retrieved July 2017, from http://www.statcan.gc.ca/tables-tableaux/sum-som/l01/cst01/labr71c-eng.htm.

StatCan (Statistics Canada). (2017o). *CANSIM Table 358-0024. Business Enterprise Research and Development (BERD) Characteristics, by Industry Group Based on the North American Industry Classification System (NAICS) in Canada*. Ottawa (ON): StatCan.

StatCan (Statistics Canada). (2017p). *CANSIM Table 477-0019. Postsecondary Enrolments, by Registration Status, International Standard Classification of Education (ISCED), Classification of Instructional Programs, Primary Grouping (CIP_PG), Sex and Student Status*. Ottawa (ON): StatCan.

StatCan (Statistics Canada). (2017q). *CANSIM Table 379-0030. Gross Domestic Product (GDP) at Basic Prices, by North American Industry Classification System (NAICS), Provinces and Territories*. Ottawa (ON): StatCan.

StatCan (Statistics Canada). (2018). *CANSIM Table 379-0031. Gross Domestic Product (GDP) at Basic Prices, by North American Industry Classification System (NAICS)*. Ottawa (ON): StatCan.

Stephan, P. E. (2010). The Economics of Science. In B. Hall & N. Rosenberg (Eds.), *Handbook of Economics of Innovation: Volume 1*. Amsterdam, Netherlands: Elsevier.

Stephan, P. E. (2012). *How Economics Shapes Science*. Cambridge (MA): Harvard University Press.

STIC (Science Technology and Innovation Council). (2015). *State of the Nation 2014: Canada's Innovation Challenges and Opportunities*. Ottawa (ON): STIC.

Stokes, D. E. (1997). *Pasteur's Quadrant: Basic Science and Technological Innovation*. Washington (DC): Brookings Institution Press.

Storey, D. J. (1994). *Understanding the Small Business Sector*. London, United Kingdom: Routledge.

Swart, A. & Granger, M. (2015). *Innovation in Mining: Canada 2015 - Developing the Right Approach to Drive Innovation in Mining*. Ottawa (ON): Deloitte.

Swart, A. & Otremba, S. (2016). *Innovation in Oil & Gas: Canada 2016 - Deloitte Top Oil & Gas Innovation Trends*. Ottawa (ON): Deloitte.

Sweeney, B. A. & Mordue, G. D. (2017). The restructuring of Canada's automotive industry, 2005–2014. *Canadian Public Policy, 43*(S1), S1-S15.

Tegmark, M. (2017). *Life 3.0: Being Human in the Age of Artificial Intelligence.* New York (NY): Random House.

The Toronto Star. (2017). New Institute Aims to Make Toronto an 'Intellectual Centre' of AI Capability. Retrieved April 2017, from https://www.thestar.com/news/gta/2017/03/28/new-toronto-institute-aims-to-be-worldwide-supplier-of-artificial-intelligence-capability.html.

Tourangeau, R. (2003). Cognitive aspects of survey measurement and mismeasurement. *International Journal of Public Opinion Research, 15*(1), 3-7.

Trosow, S., McNally, M. B., Briggs, L. E., Hoffman, C., Ball, C. D., Jacobs, A., & Moran, B. (2012). Technology transfer and innovation policy at Canadian universities: Opportunities and social costs. *Library and Information Science Publications, Paper 23,* 1-46.

Tseng, A. A. & Raudensky, M. (2015). Performances of technology transfer activities of US universities after Bayh-Dole Act. *Journal of Economics, Business & Management, 3*(6), 661-667.

UN (United Nations). (2014). *World Urbanization Prospects.* New York (NY): UN Department of Economic and Social Affairs.

UNESCO (United Nations Educational Scientific and Cultural Organization). (2018). Glossary. Retrieved February 2018, from http://uis.unesco.org/en/glossary.

UdeM (Université de Montréal). (2017). $100M for a new Quebec research cluster in AI. Retrieved December 2017, from http://nouvelles.umontreal.ca/en/article/2017/05/15/100m-for-a-new-quebec-research-cluster-in-ai/.

UofT News (University of Toronto News). (2017a). Toronto's Vector Institute Officially Launched. Retrieved April 2017, from https://www.utoronto.ca/news/toronto-s-vector-institute-officially-launched.

UofT News (University of Toronto News). (2017b). Six Degrees of Separation: How U of T's Geoffrey Hinton is Connected to Top AI Researchers Around the World. Retrieved April 2017, from https://www.utoronto.ca/news/six-degrees-separation-how-u-t-s-geoffrey-hinton-connected-top-ai-researchers-around-world.

Veltz, P. (2004). *The Resurgent City.* Paper presented at Leverhulme International Symposium, London School of Economics, London, United Kingdom.

VIDO-InterVac (Vaccine and Infectious Disease Organization-International Vaccine Centre). (2017). About Us. Retrieved July 2017, from http://vido.org/about/.

WEF (World Economic Forum). (2017). *Global Competitiveness Index 2017-2018.* Geneva, Switzerland: WEF.

West, G. (2017). *Scale: The Universal Laws of Growth, Innovation, Sustainability, and the Pace of Life in Organisms, Cities, Economies, and Companies*. New York (NY): Penguin Press.

WIPO (World Intellectual Property Organization). (2017). WIPO IP Statistics Data Center. Retrieved November 2017, from https://www3.wipo.int/ipstats/index.htm.

Wolfe, D. A. & Gertler, M. S. (2004). Clusters from the inside and out: Local dynamics and global linkages. *Urban Studies, 41*(5-6), 1071-1093.

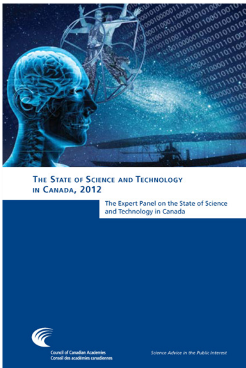
Wolfe, D. A. (2017). Why Global Innovation Supply Chains Are Going Local. Retrieved April 2017, from https://www.cigionline.org/articles/why-global-innovation-supply-chains-are-going-local.

World Bank. (2017). *Doing Business 2017: Equal Opportunity for All*. Washington (DC): World Bank.

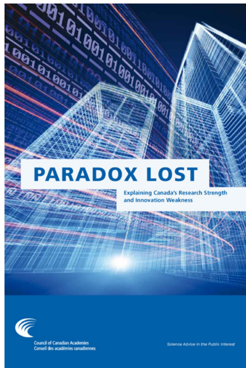
Yates, D. (2012, August 24). U of S Reaps Record Research Revenue, *The Western Producer*.

Council of Canadian Academies' Reports of Interest

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



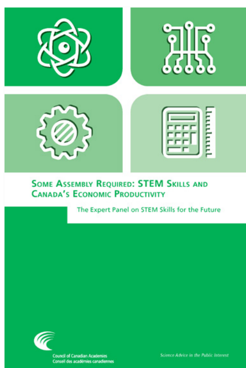
The State of Science and Technology in Canada, 2012 (2012)



Paradox Lost: Explaining Canada's Research Strength and Innovation Weakness (2013)

The State of Industrial R&D in Canada (2013)

Science Culture: Where Canada Stands (2014)



Some Assembly Required: STEM Skills and Canada's Economic Productivity (2014)

Innovation Impacts: Measurement and Assessment (2013)

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Errata

On page 43, first paragraph, second sentence: “43%” has been changed to “37%”.

On page 43, first paragraph, third sentence: “70%” has been changed to “67%”.

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