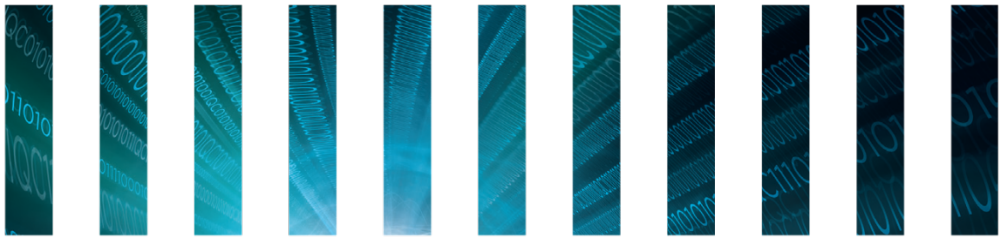

Institute for Quantum Computing

CORPORATE PLAN 2017-2018

Submitted to Ministry of Innovation, Science and Economic Development

February 20, 2018

UNIVERSITY OF WATERLOO | IQC Institute for Quantum Computing

FROM THE EXECUTIVE DIRECTOR

The Next Fifteen

IQC celebrated its first fifteen years in 2017. The incredible growth and impact of the Institute for Quantum Computing is the result of vision, commitment and collaborative partnerships focused on advancing quantum information science.

During this time, we have built a world-renowned institute, attracted 29 faculty members from around the world, and grown to a community of over 250 researchers, students, postdoctoral fellows, and technical staff. We have transformed the face of the University of Waterloo campus with the construction of the Mike & Ophelia Lazaridis Quantum-Nano Centre. Our research infrastructure enables the incredibly talented minds who are making discoveries and advancements each and every day.

Thanks to the incredible support of our partners — the Government of Canada, the Province of Ontario, the University of Waterloo and Mike and Ophelia Lazaridis —IQC has grown to be Canada's core quantum initiative. Our breadth of research, community of researchers and collaborations across the country and around the world, have made IQC a hub of quantum research and a beacon of research excellence for Canada.

As exciting as these accomplishments are, I'm more excited about what's to come in the next 15 years. Quantum information science and technology is at a turning point. Scientific advances are truly impressive and moving at a rapid pace. We are learning to harness quantum systems, exploit their power and create technologies. We are witnessing the emergence of a quantum industry in the Quantum Valley, that will accelerate in the years to come.

I can't wait to see how the next 15 years unfolds.

Sincerely,

Kevin Resch
Interim Director
Institute for Quantum Computing
University of Waterloo

EXECUTIVE SUMMARY

The Institute for Quantum Computing (IQC) at the University of Waterloo has grown to one of the top quantum institutes around the globe, conducting world-leading research in areas of quantum computing, quantum communication, quantum devices and quantum materials.

In the coming year, IQC will continue its research agenda, attract the world's best faculty, students and postdoctoral fellows to Waterloo and help position Canada to take advantage of the economic and social benefits of quantum information science. A series of targeted outcomes have been set for each of IQC's strategic objectives – all working towards IQC's overall mission to develop and advance quantum information science and technology at the highest international level.

Objectives for 2017-2018

The following list outlines IQC's objectives as noted in the 2017-2019 Contribution Agreement with the Department of Innovation, Science and Economic Development:

A. Increase knowledge in the various fields and sub-fields of quantum information, thereby positioning Canadians at the leading edge of quantum information research and technology;

B. Create new opportunities for students to learn and to apply new knowledge to the benefit of Canada;

C. Brand Canada as the destination of choice for conducting research in quantum technologies in order to attract the best in the world to Canada, create and strengthen partnerships with the international quantum information science community and promote world-class excellence in quantum information science and technology;

D. Enhance and expand the Institute's public education and outreach activities to effectively promote science and quantum information science and demonstrate how research in quantum information science can be applied; and

E. Increasingly translate research discoveries into market-ready quantum-based products which will have economic and social benefits for Canada.

Expected Results for 2017-2018

The following list outlines the expected results as noted in the 2017-2019 Contribution Agreement with the Department of Innovation, Science and Economic Development:

- Increase knowledge in quantum information science and technology;
- Support and create opportunities for students to learn and apply new knowledge;
- Brand Canada as a place to conduct research in quantum information technologies;

- Increase awareness and knowledge of quantum information science and technology and the Institute in both the scientific community and amongst Canadians more generally; and
- Position Canada to take advantage of economic and social benefits of quantum information science through seizing opportunities to commercialize breakthrough research.

ACHIEVEMENT HIGHLIGHTS 2016-2017

Over the past year, IQC completed the planned activities and targeted milestones as outlined in the 2016-2017 Corporate Plan to the Ministry of Innovation, Science and Economic Development Canada. The following sections highlight those milestones.

Objective A: Increase knowledge in the various fields and sub-fields of quantum information, thereby positioning Canadians at the leading edge of quantum information research and technology.

IQC's researchers advanced quantum information science and technology research by collectively publishing 141 new papers. IQC researchers also reached a collective, cumulative total of 25,426 citations. As an additional testament to the high level of research output, in 2016-2017, faculty continued to receive grants from varying bodies were recognized with accolades including, for example:

- **Raymond Laflamme**, faculty member in the Department of Physics and Astronomy, received a Discovery grant for his theoretical and experimental work in the field of quantum error correction;
- **Kevin Resch**, Canada Research Chair in Optical Quantum Technologies was awarded an NSERC Research Tools and Instruments (RTI) grant;
- **Debbie Leung**, faculty member in the Department of Combinatorics and Optimization, received a Discovery grant for her research studying the quantum effects in quantum communications and entanglement manipulation;
- **Vern Paulsen**, a faculty member in the pure mathematics department, received a Discovery grant for his research in operator algebras and quantum information;
- **Michael Reimer**, a faculty member in the Department of Electrical and Computer Engineering, also received a Discovery grant for his work with nanoscale photonic devices to store, process and transfer quantum information.

IQC was successful in continuing to grow its faculty complement to 26 members including:

- **K. Rajibul Islam**, Assistant Professor, Department of Physics and Astronomy in the Faculty of Science, joined IQC in November of 2016. He is the Principal Investigator of the Laboratory for Quantum

Information with Trapped Ions. Islam completed his Bachelor's and Master's degrees in India, focusing on the theory of statistical physics, quantum magnetism and the interaction of spins in frustrated systems. Motivated by the possibility of studying physical systems in a lab, Islam shifted to experimental research with laser-cooled trapped ions and moved to the University of Maryland, College Park to earn his PhD under the supervision of Christopher Monroe. His thesis, "Quantum Simulation of Interacting Spin Models with Trapped Ions," was recognized by the University of Maryland's Distinguished Dissertation Award in 2013. In his first three years as a postdoctoral fellow with Harvard University at the Center for Ultracold Atoms (CUA), Islam studied entanglement in ultra-cold neutral bosonic atoms in optical potentials with Markus Greiner's group. Returning his research focus to ions, this time in optical potentials created in a high quality optical resonator, Islam joined MIT as a postdoctoral researcher in Vladan Vuletic's group at CUA. At IQC, Islam's experimental research will address fundamental physics questions, concentrating on encoding and manipulating quantum information in a quantum many-body system using trapped ions.

- Crystal Senko, Assistant Professor, Department of Physics and Astronomy in the Faculty of Science, joined IQC in November of 2016. During her doctoral research in quantum information, Senko used trapped ions to simulate a quantum computational module and to create a spin chain experiment for manipulation in the lab. She earned her PhD under the supervision of Christopher Monroe at the University of Maryland. At the Center for Ultracold Atoms (CUA) as a postdoctoral fellow with Harvard University, Senko worked on the development of a photonic crystal waveguide that, when atoms are placed next to it, creates an interesting system for information transfer between atoms by the photons flowing through the photonic crystal. Senko's research at IQC focuses on using trapped ions for quantum simulations and quantum computing applications. Her work also explores qudits and how to improve the efficiency of encoding a logical unit of information using the multiple levels of a qudit.

- Jon Yard, Associate Professor, Department of Combinatorics and Optimization in the Faculty of Mathematics, joined IQC in September 2016. He is also an Associate Faculty member with the Perimeter Institute for Theoretical Physics (PI). Yard earned his doctorate under the supervision of information theorist Thomas Cover at Stanford University, where his theoretical research was focused on core questions in quantum information theory such as determining the capacities of noisy quantum

channels and networks for distributing quantum information. Gradually shifting his attention towards quantum computing, Yard moved on to postdoctoral positions at McGill University, Caltech and Los Alamos National Laboratory. At Los Alamos, Yard was awarded the Richard P. Feynman Fellowship for his work in quantum communication theory. As part of Microsoft's Research Station Q team, Yard pursued connections between algebraic number theory and quantum computing, and also looked at the classification of topological states of matter. At IQC, Yard will tackle complex mathematical problems and look for new solutions to existing problems by combining approaches from mathematics, physics, engineering and computer science.

Objective B: Create new opportunities for students to learn and apply new knowledge to the benefit of Canada, spurring innovation and investment in R&D activities through highly qualified personnel development.

Attraction of highly qualified personnel to IQC remains a consistent priority. At the end of the fiscal 2017, IQC was home to 128 graduate students – 46 Masters and 82 PhD students – on its way to a goal of 165 students. In 2017, eleven Masters and ten PhD students graduated from the collaborative graduate program in quantum information. After fielding 65 applications for postdoctoral fellowships, IQC also added twelve new postdocs to the IQC community bringing the total to 38.

Each year, IQC programs such as USEQIP (the Undergraduate School for Experimental Quantum Information Processing) attract the best and brightest undergraduate students from around the world to consider the University of Waterloo for graduate school. IQC also offers competitive Undergraduate Researcher Awards (URA) each year which gives the opportunity for undergraduates to complete work terms and conduct research.

This past year, **296 students applied to USEQIP**, a URA or a combination of both. A total of **19 students** from around the world were awarded a URA and **over 50 undergraduates** were hired for research work terms by faculty members.

Objective C: Brand Canada as the destination of choice for conducting research in quantum technologies and attract the best in the world to Canada, creating partnerships with the international quantum information community and promoting a world-class excellence in quantum information science and technology.

Each year IQC participates in, sponsors or presents at conferences to share research and encourage opportunities for collaborative research. In 2016-2017, IQC hosted three major conferences:

- RQI-North
- Quantum Innovators
- Quantum-Safe Cryptography Workshop.

IQC researchers also participated in dozens of conferences disseminating knowledge and building collaborations across the globe.

IQC's visitor program welcomed approximately **146 scientific visitors from 106 unique institutions** to exchange ideas and research in quantum information. These visitors came to IQC from across the world including from countries like China, India, Poland, Australia, Austria, Israel, South Korea, South Africa, Spain, the United Kingdom, Singapore and the United States.

Objective D: Enhance and expand the Institute's public education and outreach activities to effectively promote science and quantum information science and demonstrate how the research from quantum information science can be applied for the purpose of sustaining and attracting world-class talent.

This year IQC continued to offer established courses and develop new programming for young students, educators and the general public. These include the annual Undergraduate School for Experimental Quantum Information Processing (USEQIP), the Quantum Cryptography School for Young Students (QCSYS), Schrödinger's Class (formerly Teaching Quantum Technologies), three public lectures and an open house in conjunction with Waterloo Region Doors Open.

IQC also launched its largest outreach initiative to date – a 4,000 square foot, interactive, travelling exhibition on quantum science and technology. Opening for the first time in Waterloo Region in late 2016, QUANTUM: The Exhibition will travel to seven cities across Canada throughout 2017 as part of the Innovation 150 program, a Canada 150 Signature Initiative.

Objective E: Position Canada to take advantage of economic and social benefits of research through seizing opportunities to commercialize breakthrough research.

In the heart of Canada's Quantum Valley, IQC is uniquely situated to take advantage of the opportunities of quantum technologies. Over the past year, IQC researchers have continued to commercialize ready technologies. Two new spin-off companies have emerged from IQC research over the past year, bringing the number of total spin-off companies to seven.

ABOUT IQC

The Institute for Quantum Computing (IQC) at the University of Waterloo was founded in 2002 to seize the potential of quantum information science for Canada. IQC's vision was bold: position Canada as a leader in research and provide the necessary infrastructure for Canada to emerge as a quantum research powerhouse. Today, IQC stands among the top quantum information research institutes in the world. Leaders in all fields of quantum information science come to IQC to conduct research, share knowledge and encourage the next generation of scientists.

IQC is leading the next great Canadian technological revolution – the quantum revolution. Quantum technologies and applications developed in IQC labs create the foundation for next generation technologies based on quantum information research conducted right here in Canada.

None of this would be possible without the visionary leadership and investments of Mike and Ophelia Lazaridis, the Government of Canada, the Government of Ontario and the University of Waterloo. This strategic private-public partnership has accelerated the advancement of quantum information research and discovery, not only in Canada, but around the globe.

Vision & Mission

IQC's vision is to harness the power of quantum mechanics for transformational technologies that benefit society and become the new engine for economic growth in the 21st century and beyond.

IQC's mission is to develop and advance quantum information science and technology at the highest international level through the collaboration of computer scientists, engineers, mathematicians and physical scientists.

Strategic Objectives

IQC is guided by strategic objectives developed in partnership with the Government of Canada in 2008:

1. To establish Waterloo as a world-class centre for research in quantum technologies and their applications.
2. To become a magnet for highly qualified personnel in the field of quantum information.
3. To be a prime source of insight, analysis and commentary on quantum information.

OBJECTIVES AND EXPECTED RESULTS 2017-2018

Objective A: Increase knowledge in the various fields and sub-fields of quantum information science, thereby positioning Canadians at the leading edge of quantum information research and technology.

Increasing knowledge in quantum information is at the core of IQC's priorities. In 2017-18, IQC will continue its active research program with 26 existing faculty members while continuing to grow towards its steady-state goal of 39. Providing and maintaining state-of-the-art facilities allows for highly specialized experimentation in quantum computing, quantum communication, quantum devices and quantum materials to take place within IQC and makes IQC an attractive partner for external stakeholders.

Expected Results: Increase knowledge in quantum information science and technology.

Planned Activities 2017-2018:

- Leveraging faculty across three Faculties—Science, Mathematics and Engineering—researchers will continue IQC's collaborative and interdisciplinary research agenda in quantum computation, quantum communication, quantum sensors and quantum materials;
- Continuing to publish research results in world-leading journals;
- Recruiting up to two new faculty members;
- Recruiting up to one new research assistant professor;
- Continuing to outfit labs in the Mike & Ophelia Lazaridis Quantum-Nano Centre as new IQC members are recruited;
- Continuing to outfit and maintain the Quantum NanoFab cleanroom facility to enable fabrication of quantum-enabled technologies;
- Continuing the update and maintenance of lab space in Research Advancement Centre (RAC) buildings;
- Continuing effective and relevant relationships with current research partners;
- Seeking out new partnerships that will advance IQC's mission and strategic objectives.

Objective B: Create new opportunities for students to learn and to apply new knowledge to the benefit of Canada.

At the end of 2016-17, the University of Waterloo's collaborative graduate program in quantum information, in conjunction with the Faculties of Science, Mathematics and Engineering was home to 82 PhD students and 46 Masters students. In 2017-18, IQC will continue to work to attract the world's best talent to Waterloo and grow its programs towards the goal of 165 graduate students. In part, this will be done by hosting and sponsoring lectures, colloquia, workshops and conferences featuring leading researchers

from around the world, providing students with constant resources and opportunities for collaboration.

Expected Results: Support and create opportunities for students to learn and apply knowledge.

Planned Activities 2017-2018:

- Continuing to grow and attract the best talent to IQC's graduate programs
- Fielding at least 200 applications to the University of Waterloo/IQC graduate studies program
- Expand connections made with undergraduate programs at Ontario and Canadian universities
- Continuing to host timely, focused conferences, workshops, seminars and courses
- Hosting two major conferences
- Holding up to 10 workshops and seminars
- Jointly sponsoring up to 10 workshops and conferences with national and international partner organizations

Objective C: Brand Canada as the destination of choice for conducting research in quantum technologies in order to attract the best in the world to Canada, create and strengthen partnerships with the international quantum information science community and promote world-class excellence in quantum information science and technology.

Canada's government was among the first to recognize the potential of quantum science and as a result was among the first to invest in a significant way to research in this area. With IQC's leadership and dedication to international collaboration, Canada is poised to continue to be a leader in this area and be recognized on a global scale.

Expected Results: Brand Canada as a place to conduct research in quantum information technologies.

Planned Activities 2017-2018:

- Being a catalyst for collaborations of quantum information scientists across Canada and around the world
- Promoting collaborations through participation in national and international conferences
- Producing internationally recognized, high-calibre publications co-authored by IQC researchers
- Organizing at least four conferences that involve multidisciplinary participants
- Continuing to host visits to IQC by international scientists and academics

Objective D: Enhance and expand the Institute's public education and outreach activities to effectively promote science and quantum information science and demonstrate how the research from quantum information science can be applied for the purpose of sustaining and attracting world-class talent.

Throughout 2017-18, IQC will continue to build on its exceptional communications and scientific outreach programming. A major initiative of IQC's outreach team will be the travel of QUANTUM: The Exhibition to science centres across Canada as part of Canada's sesquicentennial celebrations. Existing programs such as USEQIP, QCSYS and Schrödinger's Class (formerly Teaching Quantum Technologies), along with public lectures, will continue throughout the year.

Expected Results: Increase awareness and knowledge of quantum information science and technology and the Institute in both the scientific community and amongst Canadians more generally.

Planned Activities 2017-2018:

- Host USEQIP (undergraduate) and QCSYS (high school) summer schools.
- Host the third annual high school teacher's workshop (now called Schrödinger's Class)
- Host public lectures.
- Travel QUANTUM: The Exhibition across Canada as part of the Canada 150 celebrations.
- Develop a pop-up exhibition to present in small venues, conferences and events
- Establish relationships with key strategic partners to further share IQC's research discoveries.
- Continue to share IQC's research through publications, web and social media outlets.

Objective E: Increasingly translate research discoveries into market-ready quantum-based products which will have economic and social benefits for Canada.

Technologies that emerge from quantum information science research have the potential to transform technology as we know it and shape Canada's role in the next technological revolution. To foster the commercialization of research, IQC will continue to develop and support commercialization activities and partnership opportunities for faculty, students and postdoctoral fellows.

Expected Results: Position Canada to take advantage of economic and social benefits of quantum information science through seizing opportunities to commercialize breakthrough research.

Planned Activities 2017-2018:

- Continuing development of an industry affiliate program

- Promoting opportunities for IQC researchers to connect with Waterloo's entrepreneurial ecosystem through networking opportunities and formal events in partnership with the broader startup networks in Waterloo Region.

2017-2018 Expected Activities Highlights

Month 2017/2018	Activity Highlights
April	Continued research activities – See Objective A on page 10 Continued recruiting activities – See Objective A on page 10 Launch Quantum Pop-Up Exhibit – See Objective D on page 12
May	Continued research activities – See Objective A on page 10 Continued recruiting activities – See Objective A on page 10 Quantum Industry Lecture Series – See Objective E on page 12 USEQIP – undergraduate summer school – See Objective D on page 12
June	Continued research activities – See Objective A on page 10 Continued recruiting activities – See Objective A on page 10 Host 15th Anniversary Event – See Objective D on page 12 Open Quantum Exhibit in Calgary – See Objective D on page 12
July	Continued research activities – See Objective A on page 10 Continued recruiting activities - See Objective A on page 10 Host Quantum in Iqaluit Conference – See Objective B on page 10 Host Women In Physics Conference – See Objective B on page 10
August	Continued research activities - See Objective A on page 10 Continued recruiting activities - See Objective A on page 10 QCSYS high school summer school – See Objective D on page 12 Quantum Key Distribution Workshop – See Objective B on page 10
September	Continued research activities - See Objective A on page 10 Continued recruiting activities - See Objective A on page 10 Quantum Innovators Workshop – See Objective B on page 10
October	Continued research activities - See Objective A on page 10 Continued recruiting activities - See Objective A on page 10 Quantum Innovators Workshop – See Objective B on page 10
November	Continued research activities - See Objective A on page 10 Continued recruiting activities - See Objective A on page 10 Tour QUANTUM: The Pop-Up Exhibit through Europe – See Objective C on page 11 Attend the Canada-India Tech Summit – See Objective C on page 11
December	Continued research activities - See Objective A on page 10 Continued recruiting activities - See Objective A on page 10 Quantum Cybersecurity Forum in Ottawa – See Objective B on page 10 Third annual teacher's workshop – See Objective D on page 12 Open Quantum Exhibit in Ottawa – See Objective D on page 12
January 2018	Continued research activities - See Objective A on page 10 Continued recruiting activities - See Objective A on page 10

Month 2017/2018	Activity Highlights
February	Continued research activities - See Objective A on page 10 Continued recruiting activities - See Objective A on page 10 Ottawa PR and Stakeholder Events – See Objective D on page 12
March	Continued research activities - See Objective A on page 10 Continued recruiting activities - See Objective A on page 10

2017-2018 Forecasted Financial Highlights

The following table outlines IQC's proposed spending for the period April 1, 2017 - March 31, 2018.

Institute for Quantum Computing
Summary of ISED / Enterprise Spending
for the year ended March 31, 2017
($000s)

	ISED	Enterprise
Research, HQP Development	3,485	21,736
Pre-Commercialization	96	974
Outreach and Communications	725	3,054
Management, Admin & Support	694	2,592
	5,000	28,356

Note: Enterprise Spending represents spending from ISED and Province of Ontario government special purpose funding, IQC operating funding, and individual faculty acquired research grants.

IQC has secured additional funding for activities as outlined in the Contribution Agreement. The Province of Ontario has provided IQC with $5M per year for five years starting in 2014.

Institute for Quantum Computing

Summary of Cash Flows

for the 3 years ending March 31, 2019

($000s)

	Actual	Forecasted	
	F'17	F'18	F'19
IQC Expenditures	28,356	43,894	45,067
Sources of Funds			
uWaterloo - all sources (Provost, Dean, Chair)	5,432	5,725	6,006
IQC Operating, Trust, & Endowments	3,386	3,053	1,759
Government of Canada	5,000	5,000	5,000
Government of Ontario	5,000	5,000	5,000
Faculty research funding	9,420	24,616	26,552
Additional grant and fundraising efforts	118	500	750
Total	28,356	43,894	45,067
Anticipated cash surplus / (requirements)	-	-	-

The University of Waterloo has no amounts owing to the Federal Government under legislation, under this agreement or any other agreement.

Appendices

Risk Assessment & Mitigation Strategies

		LIKELIHOOD		
		LOW	MED	HIGH
IMPACT	HIGH	6	8	9
	MED	3	5	7
	LOW	1	2	4

Risk Factor	Impact Score	Likelihood Score	Risk Rating	Explanation of Score	Mitigation Measures
IQC may not be able to attract high quality researchers	High	Medium	8	The market for world-class researchers is increasingly competitive with many countries making significant investments.	Pursue recruits from a wide breadth of areas of research. Offer competitive job offers/ package. Adequately promote the world class researchers and the cutting-edge facilities/ equipment at IQC. Further invest in cutting edge laboratory facilities.
Transformational technologies may render current research less relevant	High	Low	6	If IQC research is rendered less relevant, HQP and data seekers will go elsewhere	Ensure a wide breadth of research to investigate (this would differentiate IQC from its competitors) Continue applications for research funds to support leading edge equipment
IQC may not be able to recruit enough HQPs	High	Low	6	Many international HQPs come from potentially politically unstable countries (top three are Iran, China, India)	Promote IQC sufficiently. Ensure excellent research. Diversify markets/ countries from which students are recruited.
Operating constraints limit IQC's efforts to brand itself	High	Low	6	Operating constraints include limited resources (including staff), degree of flexibility	Recruit the right people/talents/ skills Develop and deliver a branding project plan Foster close working relationships with appropriate units within the university

Risk Factor	Impact Score	Likelihood Score	Risk Rating	Explanation of Score	Mitigation Measures
Search for new Executive Director	Medium	Low	3	Candidate may decline employment offer	Continue hiring process with exceptionally strong candidates; Maintain search for other eligible candidates until offer made and accepted Promote and support Interim Director in the running of IQC
Global Competition	Medium	Medium	5	Canada is faring well vis-à-vis global competition but advantages of being a first mover on quantum is starting to dissipate as more countries are spending vast amounts of research dollars in order to catch up	Pursue and attract highest calibre researchers Increase efforts to establish IQC as an authoritative source for quantum information world-wide Continue collaborations and strengthen relationships with other quantum leaders (domestically and internationally) through academic and industry partnerships
Government funding renewal declined or reduced significantly	High	Medium	8	Government quantum fatigue and unaligned priorities may result in funds being invested elsewhere. This would have a devastating impact on IQC's ability to operate and position Canada as a quantum leader on the world stage	Underscore relevance of IQC in addition to performance. Increase focus on methods of bringing in funds from private investors Continue to build strong relationships with all levels of government