Public organizations as anchors and quartermasters of innovation:

The case of ocean science instrumentalities in Nova Scotia, Canada.

By

Ryan T. MacNeil

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Approved:	Claudia De Fuentes, PhD Supervisor
Approved:	Roman Martin, PhD Examiner
Approved:	Ryan Gibson, PhD Reader
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Abstract

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Because there is a lack of empirical research on public innovation in goods, the importance of public organizations for innovation may be underestimated. I show that public organizations engage in the development of important and novel ocean science instrumentalities—instruments and techniques—in Nova Scotia, Canada. I conducted structured first-person interviews to collect data on 27 public and private organizations and the 702 possible interactive learning relationships between them. I use quantitative network analysis methods to confirm the importance of public organizations within this innovation system and to also investigate the nature of interorganizational interactive learning. I find that public organizations have greater degree centrality than private companies and that the removal of public organizations would result in greater network fragmentation than the removal of private companies. I also find that both public and private organizations perform more complex roles than suggested by the limited prior research on scientific instrumentality innovation. The majority of learning interactions between public research organizations and private companies in this network are symbiotic—multiplex and bidirectional. The most important relationships in the network involve bidirectional learning partnerships. These findings contradict the oversimplified view of innovation as linear market transactions. My work reinforces calls for goods to be included in studies of public innovation, makes several methodological contributions that can be used to reveal dark innovation, and identifies the anchoring and quartermastering roles that appear present in this particular scientific instrumentalities innovation system. I also highlight a potentially problematic disconnect between ocean science policies and ocean industry policies in this region.

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Preface: A Note on Style

Before introducing this dissertation, I would like to answer some objections that might be raised about its style. Those approaching this work from certain disciplines such as economics will find my use of first-person pronouns problematic. They may feel that writing in the third-person keeps research objective and scientific. But, like the academic writing experts Gerald Graff and Cathy Birkenstein (2017), I disagree. Graff and Birkenstein (2017) argue that third-person pronouns do not directly reduce subjectivity, but first-person pronouns do directly improve the clarity of an author's arguments. This is consistent with the latest style guides of the American Psychological Association (2010) and the Modern Languages Association (Gibaldi, 2008). Both guides encourage the use of first-person pronouns to avoid ambiguity around an author's voice. The most important stylistic move in this dissertation is my use of first-person pronouns to signify my position and my voice.

Readers approaching from other disciplines such as industrial and organizational psychology might be objecting to my writing style for another reason. They may be expecting a more formulaic and standardized style of presentation. They might be satisfied with the way that my results are presented in Chapter 6. However, the style, structure, and sequencing of other chapters might appear abnormal from their perspective. Some readers might immediately understand the term "analytical framework" that is used in Chapter 4. Or, like me, they might need time to consider why such a section is a meaningful and important bridge between theory and method. All readers will approach this work with expectations about the conventions of academic writing. Disciplinary conventions are increasingly evident in innovation studies. The irony is that this reduces novelty across studies whose subject matter is innovation. Ben Martin has warned that important contributions to innovation studies are now experiencing a “rough ride” through peer review because of overly strict adherence to disciplinary conventions and the expectation of a “fairly standard form” of academic writing (B. Martin, 2016, p. 440).

The challenge of writing in an interdisciplinary field like innovation studies is the presence of several competing stylistic conventions. It is difficult to hold an interdisciplinary dialogue about innovation when scholars from economics, geography, sociology, psychology, and management and organization studies all expect the conversation to take a different form. Leading thinkers in innovation studies have noticed this and warned that we must avoid the “disciplinary sclerosis” or rigidity that would come from standardizing and normalizing the field (Fagerberg, Martin, & Andersen, 2013; B. Martin, 2013). Instead, we must risk the accusation that innovation research is less legitimate than established disciplines; we must accept that it looks like an interdisciplinary “mongrel” (Fagerberg et al., 2013, p. 11). As a result, we will be in a better position to achieve novelty and relevance (Fagerberg et al., 2013; B. Martin, 2013).

This does not necessarily mean breaking all norms of academic writing. In fact, this dissertation follows the manuscript standards set out by the APA (2010), the writing patterns and templates developed by Graff and Birkenstein (2017), and the inspiration provided by my favourite writer in the field, Marianna Mazzucato (2013a). So, it is not that this dissertation lacks a consistent and legitimate style. Rather, the challenge is that this style sits at the intersection of several competing disciplinary conventions. Elements of my style will appear familiar to one reader but unfamiliar to another. Regardless of stylistic preferences, I expect that all readers will find the substance of this work novel, provocative, and compelling.

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Acronyms & Abbreviations

ACOA	Atlantic Canada Opportunities Agency
ADOT	Advanced Diploma in Oceans Technology (NSCC)
ATEI	Acadia Tidal Energy Institute
BIO	Bedford Institute of Oceanography
Co	Private Company
COVE	Centre for Ocean Ventures & Entrepreneurship
Dal	Dalhousie University
${}^{D}F$	Distance-weighted Fragmentation
DFO	Department of Fisheries and Oceans
DRDC	Defense Research and Development Canada (Formerly DREA)
DREA	Defence Research Establishment Atlantic (Formerly NRE, now DRDC)
HR	Human Resources
IORE	Institute for Ocean Research Enterprise
IP	Intellectual Property
IPR	Intellectual Property Rights
KAU	Kind-of-Activity Unit
MEOPAR	Marine Environment Observation Prediction and Response (Network Inc.)
NAICS	North American Industrial Classification System
NCE	National Centre for Excellence
NIS	National Innovation System
NOAA	National Oceanic and Atmospheric Administration (US Dept. Commerce)
NPM	New Public Management
NRCan	Natural Resources Canada
NRE	Naval Research Establishment (est. 1940 – renamed DREA)
NS	Nova Scotia
NSBI	Nova Scotia Business Inc.
NSCC	Nova Scotia Community College
NSRF	Nova Scotia Research Foundation (1949-1995, renamed to InNOVACorp)
OECD	Organization for Economic Cooperation and Development
OERA	Offshore Energy Research Association
OTCNS	Ocean Technology Council of Nova Scotia
OTN	Ocean Tracking Network
PRO	Public Research Organization
PRO-I	PRO-Industry (Interaction)
R&D	Research & Development
RIS	Regional Innovation System
SONAR	Sound Navigation and Ranging
SIC	Standard Industrial Classification
SNA	Social Network Analysis
SMU	Saint Mary’s University
STS	Science & Technology Studies
U-I	University-Industry (Interaction)
VDS	Variable Depth SONAR

Chapter 1: Introduction

In this dissertation, I argue that the importance of public organizations for innovation is underestimated. There is a burgeoning literature on public innovation—i.e., innovation undertaken by public organizations (see a review in De Vries, Bekkers, & Tummers, 2016), but public innovation in goods remains remarkably underexplored. In this opening chapter, I discuss the lack of research on public innovation in goods and argue that it is related to neoliberal beliefs about the role public organizations should play in society. Neoliberalism is the philosophy that individual well-being is best achieved by a free market and that “state interventions in markets (once created) must be kept to a bare minimum” (Harvey, 2007, p. 2). Recent discussions have highlighted problems arising from “neoliberal bias” (Cooke, 2016; Fløysand & Jakobsen, 2011), neoliberal “dogma,” “ideas,” and “strategies” (Lundvall, 2016), “neoliberal forces” (Archibugi & Filippetti, 2017), “neoliberal hegemony” (Cooke, 2016), and “market bias” (Cruz, Paulino, & Gallouj, 2015; Gallouj & Zanfei, 2013) in innovation studies and related public policies. I add to these discussions by challenging the neoliberal belief that public organizations do not produce novel and highly technical goods.

However, I do not intend to either suggest or imply that there is a conscious and explicit neoliberal bias in innovation studies. On the contrary, in this opening chapter I acknowledge that research in innovation studies deals extensively with the importance of the public sector for innovation. There is a particularly strong and explicit focus on public policy for innovation (e.g., Lundvall & Borrás, 2005). My work extends research on public innovation by emphasizing the understudied phenomenon of public innovation in goods. I argue that public innovation in goods is unconsciously concealed by latent neoliberal assumptions in our theoretical and analytical frameworks.

Over the coming chapters, I will outline the theoretical, contextual, and analytical frameworks that allow me to examine the importance of public organizations for innovation in one field of novel and highly-technical goods. I thereby contribute to two of Ben Martin's (2013, 2016) grand challenges in innovation studies: the entrepreneurial state challenge and the dark innovation challenge. By adjusting the ways that public innovation—or "the entrepreneurial state" (Mazzucato, 2013a)—is studied, I reveal public innovation in goods as a kind of "dark innovation" (B. Martin, 2013, 2016) that is often acknowledged but rarely studied.

Achieving this goal will be difficult because neoliberal ideas are widely—but unconsciously—applied to large numbers of public organizations. These organizations are often subsumed under one label: "the state" or "government." But to ensure clarity in this dissertation, I do not take an omnibus approach to the public sector. I follow OECD (2005) guidelines by defining organizations as standalone legal entities or a kind-of-activity units (KAUs) (see further discussion in Chapter 4 and definitions in the Glossary at the end of the text). Furthermore, I use a theory-driven approach—from the work of James Perry and Hal Rainey (1988)—to distinguish between public and private organizations. Perry and Rainey (1988) identified three features that might make an organization "public": public ownership, public funding, and polyarchal control—i.e., democratic rather than market-based control. These three markers—ownership, funding, and control—can be combined in a number of ways to create a typology of different public and private organizations. Alignment of any two or more criteria tips the balance toward the public or private end of a continuum. An organization should therefore be considered "public" if it is "privately" incorporated but nonetheless publicly-funded and subject to democratic control (Perry & Rainey, 1988)[1]. Such definitions are required to avoid treating all public organizations as one homogenous—and passive—actor.

Based on neoliberal ideas, the actions of public organizations are typically labelled as "interventions" in the marketplace (Breimyer, 1991; Mazzucato, 2016). Indeed, public organizations are thought to be at their best when they interact with the market minimally, and only when they are correcting market failures. Public organizations are seen as necessary for innovation because they provide regulatory frameworks, some knowledge inputs, and a rich customer-base for new capital goods. However, public organizations are not often seen as active innovators (Koch & Hauknes, 2005; Mazzucato, 2013a; Windrum & Koch, 2008). Indeed, it has been said that public organizations are "conspicuously missing" from analyses of new product and process development (Koch & Hauknes, 2005). They do not appear in Joseph Schumpeter's *Mark I* and *Mark II* innovation patterns, where creative destruction is achieved through the efforts of private entrepreneurs or large firms but not public organizations. They are also not found in Keith Pavitt's (1984) famous taxonomy of innovation, or the subsequent adaptations (e.g., Archibugi, 2001; Castellacci, 2008). These frameworks only classify the innovation patterns of private firms or industries (MacNeil, 2014a). Pavitt (1984) did suggest that another category might be needed in his taxonomy "to cover purchases by government

[1] See the glossary for detailed definitions of "organization," "public organization," "private organization" and other key concepts in this dissertation.

and utilities of expensive capital goods related to defense, energy, communications and transport" (p. 370). In other words, it was not important to include public organizations in the original taxonomy because they do not produce innovation; they merely purchase it from the private sector. Given the assumption that public organizations do not innovate, it is acceptable to exclude them from innovation classification schemes. Indeed, public organizations are often described as the opposite of innovative (Mazzucato, 2013a; Windrum & Koch, 2008). Active innovation by public organizations continues to be underexplored in innovation studies (De Vries et al., 2016; Fagerberg et al., 2013; Holbrook, 2010; Mazzucato, 2013a). Instead, private companies are seen as the central actors in innovation dynamics; this has been described as a "market bias" (Cruz et al., 2015).

The Public Innovation in Goods Gap

Many studies have contradicted this bias by investigating innovation in public services and public policy (Altshuler & Behn, 2010; Bason, 2010; Fuglsang, 2010; Gallouj, Rubalcaba, & Windrum, 2013; Røste, 2005; R. M. Walker, 2014; R. M. Walker, Jeanes, & Rowlands, 2002; Windrum & Koch, 2008). However, a small piece of neoliberal myopia remains: there is very little research on public innovation in goods. Indeed, most studies of public innovation do not collect data on innovation in goods (Arundel & Huber, 2013). In the following paragraphs, I unpack this gap in the public innovation literature and identify several inconsistencies in discussions about public innovation in goods. I then return to the idea that this gap is related to neoliberal ideas about public versus private production of goods.

Many publications in this field acknowledge that public organizations produce innovative goods without empirically investigating this type of innovation (e.g., Bloch, 2011; De Vries et al., 2016; Demircioglu & Audretsch, 2017; Gallouj et al., 2013; Halvorsen, Hauknes, Miles, & Røste, 2005; Hartley, 2005; Koch & Hauknes, 2005; Mazzucato, 2013a; R. M. Walker et al., 2002; Windrum & Koch, 2008). For example, a prominent book in the field begins with a chapter that mentions public innovation in medical technologies, instruments, and drugs (Windrum & Koch, 2008). The same book concludes with the surprisingly definitive counter-claim that “technological innovations, especially goods, are the exclusive domain of the private sector” (Windrum & Koch, 2008, p. 239). Another prominent book on public innovation provides multiple examples of technological goods that were developed by public organizations in its opening two pages, but then focuses exclusively on services for the remainder of its length (Gallouj et al., 2013). In a similar vein, two different taxonomies of public innovation exclude goods after providing examples of public innovation in goods on a preceding page (Halvorsen et al., 2005; Koch & Hauknes, 2005). The decision to exclude goods is explicit in another paper where the argument is that “product innovation” is “problematic in the public sector, where *many* [emphasis added] innovations are service-based” (R. M. Walker et al., 2002, p. 203). These examples all contain an interesting contradiction: goods are present in anecdotal discussions of public innovation but not in empirical analysis.

Another interesting contradiction is found in research on “The Entrepreneurial State” (Lazonick & Mazzucato, 2013; Mazzucato, 2013a, 2013b, 2013c, 2015, 2016; Mazzucato & Penna, 2016). Marianna Mazzucato is perhaps the most prominent critic of neoliberal ideas about public innovation. In her book, *The Entrepreneurial State*, she describes the mythology around public innovation as a “discursive battle” (Mazzucato, 2013, p. 2) about whether “the state” is capable of playing an entrepreneurial role in society. To demonstrate that the state is highly entrepreneurial, Mazzucato (2013) presents anecdotal examples of radical innovations—particularly goods—that emerged from mission-oriented public innovation projects. In Chapter 5 of her book, she argues that “there is not a single key technology behind the iPhone that has not been State-*funded* [emphasis added]” (Mazzucato, 2013a, p. 11). I agree with the conclusion that all of the key iPhone technologies were developed using public funds. However, I worry that focusing on the state’s financial role may shift attention away from other active roles performed by public organizations.

The broader entrepreneurial state research program is focused on financial mechanisms. Both before and after the publication of *The Entrepreneurial State*, this research has been focused on questions of financing and risk in innovation (Lazonick & Mazzucato, 2013; Mazzucato, 2013b, 2013c, 2017; Mazzucato & Penna, 2016; Mazzucato & Semmler, 2002; Mazzucato & Tancioni, 2008). This is important work; however, the examples provided in the iPhone chapter of *The Entrepreneurial State* (Mazzucato, 2013a) are not exclusively about public funds being spent to stimulate private innovation. These technological goods were not all the result of state-funding to private companies; some were the work of public organizations. Several examples are provided of iPhone elements that were invented within public organizations and then commercialized (Mazzucato, 2013a). There is also discussion of two prominent examples where technological goods were developed by public organizations initially for the exclusive use of other public organizations: the global position system (GPS) and the speech interpretation and recognition interface (SIRI) virtual assistant (Mazzucato, 2013a). GPS technology was developed within the American military in the 1970s and did not enter civilian use until the 1990s (Mazzucato, 2013a). SIRI was developed by publicly-paid university researchers for use by the CIA beginning in 2000[2] and not commercialized for civilian use until 2010 (Mazzucato, 2013a). Certainly, public funds were expended in these efforts. But because the focus of this research is on financial mechanisms, it is easy to miss the point that these anecdotes are about technologies that were developed by employees of public organizations. Overall, the entrepreneurial state research agenda is focused on certain public innovation roles; an individual public organization might act as: “a spender, facilitator, and regulator, but also as an investor and venture capitalist” (Mazzucato, 2016, p. 144). Like the taxonomies of public innovation discussed above, this list of roles does not leave room for the development of goods. The empirical focus on public finance for innovation suggests that, although public money is often involved, radical innovation in goods happens outside public organizations. Research on the entrepreneurial state has contributed greatly toward dispelling neoliberal dogma, and yet public innovation in goods remains underexplored.

Several pieces of scholarship do attempt to incorporate goods into research on public innovation. The first two of these contributions—the taxonomies of public innovation developed by Jean Hartley (2005) and De Vries et al. (2016)—both make

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[2] Note that SIRI was developed by a research unit at Stanford University. Stanford is commonly referred to as a “private” university in the US system, but it should be treated as a “public” organization for research purposes according to the theoretical criteria developed by Perry and Rainey (1988).

allowances for public innovation in goods. De Vries et al. (2016) include goods in their taxonomy of public innovation but do not provide any specific examples in their discussion. Hartley (2005) includes goods in her taxonomy and provides the anecdotal example of public innovation in medical devices. Interestingly, however, both of these contributions turn their attention away from innovation in goods and toward innovation in services. De Vries et al. (2016) note that this is the normal thing to do. They say, “the dominant focus in the body of empirical knowledge on public sector innovation is on internal administrative, often technology driven processes” (De Vries et al., 2016, p. 152). This explanation confirms that public innovation research is focused on service and process innovations, but it does not explain the scant empirical research on public innovation in goods.

Some attempts have been made to measure public innovation in goods (Arundel & Huber, 2013; Bloch, 2011; Bloch & Bugge, 2013; Bugge, Mortensen, & Bloch, 2011; Demircioglu & Audretsch, 2017). In three of these cases, researchers define product innovations as both goods and services but report only aggregate/combined product innovations (Bloch, 2011; Bloch & Bugge, 2013; Demircioglu & Audretsch, 2017). In two other cases, researchers report data on public innovation in goods but provide cautious interpretations (Arundel & Huber, 2013; Bugge et al., 2011). The first of these—a large-scale study across various Nordic countries—found that 12%-34% of public organizations had introduced innovations in physical goods (Bugge et al., 2011). However, the authors suggest that these numbers are “rather high” and that the goods may be parts “of larger innovations in the public services” (Bugge et al., 2011, p. 31). The second—a study of innovation in Australian public organizations—found that one-third of interviewees and 21.3% of survey respondents had introduced innovations involving a tangible good or software (Arundel & Huber, 2013). The authors of that study are quick to point out that none of their respondents described the goods innovations as "important" or "successful" and that the respondents tended to view goods "as a type of service" (Arundel & Huber, 2013, p. 156). In this way, both studies are somewhat dismissive of their data on public innovation in goods. Overall, there are some studies that measure public innovation in goods but there is no focused research agenda on the subject.

The preceding paragraphs speak to a gap in the research on public innovation. Consistently, research on public innovation skims over the subject of public innovation in goods. In the examples provided above, public innovation in goods is either ignored, dismissed, minimized, or not seen as an important research focus. The public innovation literature includes anecdotes about novel inventions to convince readers that public organizations innovate, but then treats these anecdotes as extraordinary and abnormal. Many studies of public innovation notice public innovation in goods (e.g., Bloch, 2011; De Vries et al., 2016; Demircioglu & Audretsch, 2017; Gallouj et al., 2013; Halvorsen et al., 2005; Hartley, 2005; Koch & Hauknes, 2005; Mazzucato, 2013a; R. M. Walker et al., 2002; Windrum & Koch, 2008), but very few engage in research about it (e.g., Arundel & Huber, 2013; Bugge et al., 2011). The literature is focused nearly entirely upon innovation in public services; and, it has been said this focus is an important response to the otherwise dominant focus on certain consumer technologies (e.g., computer electronics) in innovation studies (Osborne & Brown, 2011, 2013)—the "boys' toys" bias (B. Martin, 2013, 2016). I agree that the boys' toys bias is a problem across innovation studies, but it appears that this bias has been inverted in research on public innovation. Subsequently, public innovation in goods in underexamined.

It is possible that public innovation in goods is understudied because private companies are thought to be the only appropriate producers of goods (e.g., Windrum & Koch, 2008, p. 239). There are some hints at this in the literature. For example, it has been said that the "appropriate" way to understand product innovation in the public sector is by focusing on services (R. M. Walker, 2014, p. 23). This implies that goods are the inappropriate way to understand product innovation in the public sector. Adam Holbrook (2010) notices this norm and hints at the underlying neoliberal discourse. He says, "public discourse on the role of the state in the economy and society has, in many developed countries, demanded that the state withdraw from some service industries and virtually all goods producing industries" (Holbrook, 2010, p. 161). If public organizations have indeed withdrawn from the production of goods, then I might agree that it is appropriate not to study public innovation in goods. However, I agree with Anthony Arundel and Dorothea Huber (2013) that goods should be included in the measurement of public innovation. They suggest that the exclusion of goods is the result of widely held beliefs about public organizations: "data on product or goods innovations are not collected in most studies because of the belief that the public sector rarely develop and or implement new types of goods, with the focus primarily on services" (Arundel & Huber, 2013, p. 149). Such beliefs mean that most innovation measurement methods and instruments are not designed to capture public innovation in goods. I therefore propose that public innovation in goods is what Ben Martin (2013, 2016) has called "dark innovation."

The Dark Innovation Challenge

Martin (2016) developed the concept of dark innovation using the analogy of dark matter. Astronomers are aware that dark matter exists, but they cannot directly observe it with current instruments. Extending the analogy to innovation studies allows us to speak about dark innovations, which Martin defines as “types of innovations [that] have been ignored or are essentially ‘invisible’ in terms of conventional indicators” (B. Martin, 2016, p. 434). I propose that public innovation in goods is an area of dark innovation; I argued above that its existence is acknowledged in the literature, but it is often empirically ignored. In this section I will consider where and how public innovation in goods might be made visible. To further extend the dark matter analogy, this section is about adjusting my instruments so that this dark innovation can be observed.

Where might public innovation in goods be observed? To observe public innovation in goods, I can focus on an innovation context—a region and/or sector—where it might be particularly concentrated. Based on common beliefs about public innovation, it would be normal to assume that such a context would be extreme or unique and therefore unworthy of investigation. However, I have argued above that public innovation in goods is frequently noticed. Therefore, it is not necessarily rare. Conducting research in such a context could confirm the existence of this dark innovation and reveal some of its qualities. In his authoritative textbook on case study research, Robert Yin (2009) explains that such contexts are so valuable for social science that they warrant a single-case design. He explains that when researchers have access to a context in which it is possible to “uncover some prevalent phenomenon previously inaccessible to social scientists, such conditions justify the use of a single-case study on the grounds of its revelatory nature" (Yin, 2009, p. 49). This dissertation therefore presents an in-depth investigation of a single case study situated within a field where I might expect to find public innovation in goods: the field of scientific instruments.

There is a limited literature on scientific instrument innovation. Several important contributions in innovation studies have theoretically discussed scientific instruments without collecting empirical data (de Solla Price, 1984; Kline, 1985; Kline & Rosenberg, 1986; Rosenberg, 1992). Meanwhile, there have been very few empirical studies of scientific instrument innovation. In one such study, Nick Oliver and Michelle Blakeborough (1998) examine new product development networks in the private sector and aggregate their results across six types of products—including scientific instruments. They do not analyze scientific instruments separately from five other types of products. The only studies to focus empirically on scientific instrument innovation were conducted by Eric von Hippel and his colleagues (Riggs & von Hippel, 1994; Spital, 1979; von Hippel, 1976, 1988). Spread over nearly twenty years, their research consistently demonstrated that the users of scientific instruments—the scientists themselves—perform nearly all of the activities involved in developing scientific instruments. Based on these findings, von Hippel asserted that the "locus of innovation" (von Hippel, 1976) for scientific instruments is the scientist user, not the instrument manufacturer. Indeed, this line of research concluded that instrument manufacturing companies were only making incremental improvements to existing technologies (Riggs & von Hippel, 1994; Spital, 1979).

After publishing one article (von Hippel, 1976), incorporating that article into his first book (von Hippel, 1988), and supervising related work by a PhD student (Spital, 1979), von Hippel (1988) dismissed scientific instruments as a context not worthy of further investigation. Six years later he revisited this context in a fourth and final publication (Riggs & von Hippel, 1994). He otherwise shifted the focus of his career to what he called “other, more ‘normal’ fields” (von Hippel, 1988, p. 20).[3] His early career focus on scientific instrument innovation provided evidence of a new phenomenon—user innovation—opening an important line of research (Bogers, Afuah, & Bastian, 2010; von Hippel, 1986, 1988, 2005). I open another line of research by arguing that these studies by von Hippel and his colleagues also provide evidence of public innovation in goods: scientist-users are often employed within public organizations.

I concede that not all scientists work for public organizations. But scientific norms, as much as they have changed in the past century (Gibbons, 1994, 2000; Helga Nowotny, Scott, & Gibbons, 2003; Helga Nowotny, Scott, & Gibbons, 2013; Ziman, 1996), still mean that most scientists are employed by public research organizations (PROs)—public organizations that perform scientific research, such as universities and government laboratories (see also definition in the Glossary). Early studies of scientific instrument innovation do not use the words “public” or “government” (see Spital, 1979; von Hippel, 1976, 1988). Only the most recent contribution of the set (i.e., Riggs & von Hippel, 1994) acknowledges that some of the scientist-users were public employees. Of the 24 user innovations sampled by Riggs and von Hippel (1994), 15 were developed at universities,

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[3] I concede that this context is different from those normally studied by innovation scholars. But it is the unusual and understudied nature of this context that holds the potential for novel observations. This is the advantage of revelatory case contexts (Yin, 2009).

four at government laboratories, and nine at corporate research laboratories. The authors do not distinguish between public and private universities, but their data was collected in the United States where the differences between public and private universities have been extensively debated, particularly in the legal community (see O'Neil, 1969). In an extensive review of this distinction, legal scholar Robert O'Neil (1969) concludes that "most private colleges and universities are public to some degree" (p. 188). Perry and Rainey (1988) suggest differences between public and private universities, but O'Neil (1969) argued that the only thing truly private about private universities is their ownership structure. By the 1960s, most so-called "private universities" in the USA were subject to public control and were receiving public funds at a per student rate that was twice as high as so-called public universities (O'Neil, 1969). Under the criteria developed by Perry and Rainey (1988) and the legal arguments presented by O'Neil (1969), nearly all universities should be classified as public organizations[4]. This means that upwards of two-thirds of the cases studied by Riggs and von Hippel (1994) could have been instances of public organizations producing scientific instrument innovations.

One study has linked the work of von Hippel and his colleagues with the subject of public innovation (i.e., Dalpé, 1994). However, the focus of that study is on the procurement activities of public organizations. This procurement focus it implies that public organizations purchase—or pays for—innovation from the private sector. This is

[4] The public nature of universities is less contested in Canada where only a small number of higher education institutions have private ownership structures (see Holdaway, Newberry, Hickson, & Heron, 1975). Based on all three Perry and Rainey (1988) criteria, all ten universities in the Province of Nova Scotia are public.

similar to the limitation of Mazzucato's focus on finance. When I further unpack the work of von Hippel and his colleagues in Chapter 2 it will become clear that they were not observing innovation-by-procurement. A careful read of their results points to the development of new technological goods, primarily inside public organizations. Their "scientist-users" were producing and disseminating multiple fully-functional scientific devices (Riggs & von Hippel, 1994; Spital, 1979; von Hippel, 1976, 1988). Scientist users were more than customers of private manufacturers, they were producing scientific instruments. This suggests that public organizations could be the "locus of innovation" (von Hippel, 1976) for scientific instruments. However, this possibility is not considered in the existing studies of scientific instrument innovation. Studying public innovation in scientific instruments could therefore extend the limited research on scientific instrument innovation. Furthermore—and more germane to this dissertation—studying scientific instruments could address the gap in research on public innovation in goods.

Scientific instruments or instrumentalities? Before proceeding any further, I must highlight a major risk of discussing innovation in scientific instruments. By focusing on instruments—which are physical goods—I would be treating goods and services as dichotomous categories of product innovation and then privileging goods. This would see me perpetuate the production bias that has been critiqued by leading scholars of public innovation (i.e., Osborne & Brown, 2011) and the "boys' toys" bias that plagues innovation studies (see B. Martin, 2013; B. Martin, 2016). Fortunately, this problem can be resolved by following Derek de Solla Price's (1984) shift from the narrow language of "scientific instruments" to his broader concept: "scientific instrumentalities." As one of the past century's preeminent scholars of science, de Solla Price (1984) argued that it is not theoretically appropriate to narrowly focus on scientific instruments because the technologies of science take many forms. He defined an “instrumentality” as any “laboratory method” or scientific technique, including techniques that are embedded in physical instruments and those that are tacit. A scientific instrument is a piece of scientific know-how—a scientific instrumentality—that has been codified into a physical artifact. These scientific instrumentalities would be considered goods. Other pieces of scientific know-how might be codified in other ways—such as in scientific publications—or they might remain tacit. In this way, scientific know-how can be delivered as a service (de Solla Price, 1984; Hughes, 1976). New scientific instruments and techniques can be produced as goods or services; they can be product innovations. Ultimately, instrumentalities are defined by their application: they are the process innovations of science.

De Solla Price’s (1984) shift from “instruments” to “instrumentalities” is strikingly similar to the way that marketing scholars have overcome their production bias. One of the principles of the “service-dominant logic” in marketing is that goods should be thought of as services-embedded-in-objects (Vargo & Lusch, 2004, 2008). For example, customers purchase dishwashers because these objects perform a cleaning service. The service-dominant logic tells us that all goods perform services (Vargo & Lusch, 2004, 2008). But there is no such service-dominant logic in innovation studies. Here, goods and services are commonly considered to be separate and discrete categories (Barras, 1986; OECD, 2005). I could conform to this norm, focus on the tangible technologies of science—the instruments—and use this context to investigate public innovation in goods. But a better option is to focus on instrumentalities: the techniques and methods of science which are sometimes performed by scientific instruments. Use of this term avoids a production bias, while still focusing attention on a field that is likely to include public innovation in goods. I therefore refer to “scientific instrumentalities” and “ocean science instrumentalities” throughout this dissertation, except when referring to the work of von Hippel and his colleagues who spoke only of “instruments” (Riggs & von Hippel, 1994; Spital, 1979; von Hippel, 1976, 1988).

How might public innovation in goods be observed? Based on the forgoing, one might reasonably expect to observe public innovation in goods and services in the field of scientific instrumentality innovation. Having identified this broad empirical context, I am now able to ask a very pointed research question: How important are public organizations for scientific instrumentality innovation? In posing this question, my objectives are to (1) confirm that public organizations produce technological goods, (2) investigate the relative importance of public and private organizations for scientific instrumentality innovation, and (3) understand the relationships between public and private organizations for scientific instrumentality innovation. Chapter 3 provides detailed discussion and a brief history of the specific empirical context in which I investigate my research question—the field of ocean science instrumentalities innovation in Nova Scotia, Canada. But as with other instances of dark innovation (see discussion in B. Martin, 2013, 2016), investigating this phenomenon first requires some adjustments to our social science instrumentalities. In this section, I discuss the ways that various theoretical and analytical mechanisms make public innovation in goods more or less visible. By doing so, I make important contributions to the dark innovation challenge (B. Martin, 2013, 2016).

My challenge begins with the linear innovation model that von Hippel and his colleagues used. Under this model, the development of scientific instruments is thought to follow a series of sequential steps from problem identification to commercialization. Innovation is theoretically framed as a linear product development process. This linear model and its many limitations will be discussed in Chapter 2. For now, let us focus on its market-orientation. Under different variations of this model, innovations are thought to be either pushed by knowledge suppliers or pulled by forces of market demand. Regardless of the direction—the push or pull—the market is seen as the final destination for new products. The key relationships in the process are market exchanges between users and producers. Users and producers can perform different product development functions—different steps in the process—but they are ultimately related to one another through a market exchange. Theoretically tying innovation to the market obscures some forms of public innovation. Recent discussions (e.g., Bloch & Bugge, 2013; Gault, 2012, 2018), have suggested that it should be sufficient for innovations to be implemented in any way—e.g., "made available to potential users" (Gault, 2018, p. 619)—and not necessarily "introduced on the market" (OECD, 1992, 2005).[5]

[5] Some readers might object to equal treatment of public goods and private goods—those products that enter the market and those that do not. I grant that product innovations entering the market appear more valuable because they have exchange value, whereas common and public goods are, by their very nature, excluded from market exchange. However, this does not mean that such goods are without value. It simply means that they must be valued differently (see Lamont, 2012; Mazzucato, 2017). I follow Gault (2012) and Bloch and Bugge (2013) in challenging the common statistical standard that innovations must be introduced "onto the market" (OECD, 2005).

The shift away from linear models has been one of the most important advancements in innovation studies (B. Martin, 2013, 2016). This shift began with the introduction of the “chain-link” model in the late 1980s (Kline, 1985; Kline & Rosenberg, 1986). The chain-link model emphasized knowledge pathways rather than market transactions, but it nonetheless maintained that innovations are introduced onto the market. When I unpack this model in Chapter 2, I highlight interesting—if fleeting—references to innovation in scientific instruments. I also discuss the problematic dichotomy between research and development that is found in the chain-linked model (Caraça, Lundvall, & Mendonça, 2009). Public organizations have tended to be positioned on the research side of the dichotomy while private firms have been given the leading role on the development side. In short, the shift away from linear models and toward a chain-link model has not been a departure from a market-orientation.

However, there is potential to develop alternate perspectives using the innovation systems approach. Beginning in the 1990s, innovation studies began to shift away from the chain-link model and toward the innovation systems approach (C. W. Freeman, 1987; Lundvall, 1992; Nelson, 1993). One of the originators of this approach, Christopher Freeman, defined an innovation system as a “network of institutions [i.e., organizations] in the public and private sectors whose activities and interactions initiate, import, modify and diffuse new technologies” (C. W. Freeman, 1987, p. 1). His definition shows us that, from its earliest days, the innovation systems approach was amenable to equal treatment of public and private organizations. And it has certainly helped to overcome prior firm-centric approaches to innovation (Fagerberg et al., 2013). This is partly because the innovation systems approach is not focused on market transactions. It does not conceptualize innovation as a function of free markets; instead, it frames innovation as an "interactive learning" process (Lundvall, 1988) that takes place within nations (C. W. Freeman, 1987; Lundvall, 1988; Nelson, 1993), regions (Asheim, Smith, & Oughton, 2011), sectors (Breschi & Malerba, 1997; Malerba, 2002), and global networks (Chaminade & Vang, 2008; Ernst, 2006; Liu, Chaminade, & Asheim, 2013). Interactive learning comprises various interorganizational processes that (re)combine knowledge (see discussion in Chapter 2 and the Glossary). In the next chapter, I discuss the many kinds of interorganizational interactive learning discussed in the literature and note that many of these do not involve market transactions. In this way, the innovation systems approach has shifted academic focus away from exchange markets and toward learning systems. The innovation systems approach, then, is the basis upon which I can carefully design theoretical and analytical lenses for the study of public innovation in goods and services.

The innovation systems approach must be used carefully in this dissertation because it is often combined with a focus on firms and markets. It has been used to observe several public innovation roles, but these have been passive ones (see discussion in Mazzucato, 2013a, 2016). Particular emphasis has been placed on understanding the ways public organizations can stimulate innovation in the market through policy (Edquist, 2001; Edquist & Chaminade, 2006), procurement (Edquist, Hommen, & Tsipouri, 2000; Edquist & Zabala-Iturriagagoitia, 2012), and mission-oriented R&D (see Foray, Mowery, & Nelson, 2012). Across these studies, the innovation systems approach is used to identify "system failures" and then prescribe intervention by public organizations (Mazzucato, 2013a, 2016). Mazzucato criticizes the innovation systems approach for this because she believes it has "indirectly perpetuated the view of the public sector as a passive force that can only facilitate change, rather than lead it" (Mazzucato, 2016, p. 141). However, as I have shown, the innovation systems approach does not default toward a market orientation.

To reveal dark innovation, I must adjust the instrumentalities that are normally used to study innovation, including those associated with the innovation systems approach. In the words of Martin, "the challenge to the next generation of [innovation studies] researchers is to conceptualize, define, and come up with improved methods for measuring, analysing and understanding 'dark innovation'" (B. Martin, 2016, p. 434). Much of my discussion in Chapters 2, 4 and 5 is devoted to this challenge. Looking for innovation outside the market requires careful adjustments to theoretical frameworks (see Chapter 2), analytical frameworks (see Chapter 4), and research methods (see Chapter 5). The innovation systems approach provides a solid base with which I can offer an alternative perspective—one that is not grounded in a market-orientation. This dissertation therefore contains considerable discussion of the concepts, definitions, measurement methods, and analytic techniques I use to evaluate the importance of public organizations for innovation in scientific instrumentalities. As I argue in the final chapter, these adjustments are, in and of themselves, an important contribution to the instrumentalities used in innovation studies.

Structure of the Dissertation

The purpose of this introductory chapter has been to understand a gap in the literature on public innovation—the public innovation in goods gap. I have argued that the existence of this gap is consistent with neoliberal ideas about the proper role for public organizations with respect to the production of goods in society. I have also argued that it is a type of dark innovation: there are many indications that public organizations produce innovative goods, but this phenomenon has barely been empirically investigated. As with other forms of dark innovation, the limited empirical research may be the result of limitations in common theoretical and analytical frameworks. These frameworks do not prevent us from anecdotally noticing technological artifacts that have been developed within public organizations. But they do help us to either turn away from the phenomenon or to observe it and then classify it as something else, e.g., user-innovation, financing of innovation, procurement for innovation, public services innovation. This appears to have been the situation in the only four empirical studies focused directly on scientific instrument innovation; it is likely that public research organizations were the locus of innovation in these studies, but their employees were labelled as users—not producers—of these innovations. The limited literature on scientific instrumentality innovation suggests that this context could provide a "revelatory" case (Yin, 2009) of public innovation in goods (and services). To investigate a context of scientific instrumentality innovation, I will need to develop theoretical and analytical frameworks that do not have a market-orientation. As argued in this chapter, I cannot presume that only private companies produce innovative goods, or that public organizations only produce service innovations. I have taken the first step in this direction already; I have argued for the importance of defining innovation as an interactive learning process and not merely a market outcome. Over the coming six chapters I will further refine my theoretical, conceptual, and analytical frameworks and make observations that address this important gap in the field.

Chapter 2 elaborates on several points already raised. It explores the current state of knowledge regarding scientific instrumentality innovation and simultaneously unpacks the theoretical models that were used to establish this knowledge. I have already noted that existing empirical work in this context has been limited to only a few contributions by von Hippel and his colleagues. Their work is therefore unpacked in some detail, as is the underlying linear model of innovation. Additional insights are then drawn from theoretical discussions about scientific instrumentalities that used the chain-link model and ones that used theory from the field of science and technology studies (STS)—a field where theory is not simplified into illustrated boxes. These strands of discussion help me to articulate three theoretical propositions about public innovation in scientific instrumentalities.

Additionally, Chapter 2 will show that theoretical understandings of innovation grow in sophistication from the 1970s to present-day, while interest in scientific instrumentalities innovation disappears. The chapter concludes by developing an appropriate theoretical framework— an innovation systems approach—for studying public innovation in a field of scientific instrumentalities. The innovation systems approach has not been used to study scientific instrumentality innovation,[6] but as I have argued above, its theoretical basis makes it suitable for examining public innovation in

[6] A comprehensive database search for "'scientific instrument*' AND 'innovation system*'" conducted in May 2017 returned many publications referencing von Hippel (1976), but no publications that applied an innovation systems approach to this field of technology. The search was conducted in Google Scholar, Business Source Premier (EBSCO), Science Direct, Sage Premier All-Access, and Taylor & Francis Journals Online.

goods. Chapter 2 will expand on the framing of innovation as interactive learning and capitalize on the flexibility of the innovation systems approach. I will adjust existing "channels of interaction" models (e.g., De Fuentes & Dutrénit, 2012) so that it is theoretically possible for public and private organizations to be equally capable of interactive learning.

Chapter 3 then describes the specific empirical context used in this dissertation: the field of ocean science instrumentalities in Nova Scotia, Canada. It begins by defining ocean science and then positioning this dissertation within the present-day circumstances of ocean science and technology innovation in the province. I argue that my research is not only important for the advancement of innovation theory, but it is also important in light of recent cuts to public organizations that perform ocean science and simultaneous investments in ocean technology industrial development. After considering the recent discord between science policy and industrial policy, I examine the histories of four public research organizations that were central to the formation of this innovation system. I conclude the chapter by considering whether my historical data supports the theoretical propositions developed in Chapter 2. This appears to be the case, and this discussion leads me to add a fourth theoretical proposition that only becomes obvious once context and theory are combined.

At the end of Chapter 3 I argue that limitations of the historical data make it insufficient to investigate my research question. Direct empirical observations are required. However, common analytical frameworks were not designed for observing public innovation in goods. Chapter 4 is therefore devoted to developing an appropriate analytical approach. The resulting analytical framework combines insights from innovation systems theory with insights about network analysis methodology to establish the boundaries of this regional-sectoral innovation system. For my analysis, this system is operationalized as an interactive learning network. To complete my analytical framework, Chapter 4 also introduces key measurement concepts from network analysis and uses these to restate the four theoretical propositions as hypotheses. As Whetten (1989) explains, theoretical propositions involve concepts but testable hypotheses require measures. The overall purpose of my analytical framework is to bridge between theory and method.

Chapter 5 then provides details of my research method. I collected data through face-to-face computer-assisted interviews with organizations involved in using and producing ocean science instrumentalities in Nova Scotia, Canada. These organizations were identified through key informant interviews with the five individuals whose positions included a responsibility for understanding and supporting the region's ocean science and technology sector. I carefully developed my data collection techniques to ensure consistent and equal treatment of public and private organizations, and constructed a network dataset so that the hypotheses from Chapter 4 could be evaluated using quantitative network analysis.

Chapter 6 provides the results from this hypothesis testing and descriptive statistics that confirm the development of technological goods within the past 5 years by all of the private companies and nearly two-thirds of the public organizations that I interviewed. The results also provide valuable insights into the types of interactive learning relationships that are important within this innovation system.

Based on these results, Chapter 7 provides some discussion of my theoretical and methodological contributions, policy implications, research limitations, and future directions. The central contribution of this dissertation arises from my direct observation of public innovation in goods and services. Not only do I find that public organizations produce innovative goods, but in direct response to my research question I find that public organizations are more important than private organizations for this regional-sectoral innovation system. These observations contradict the neoliberal ideas identified at the beginning of the dissertation. This observation also confirms the importance of my methodological contributions: the adjustments I make throughout this dissertation are effective in allowing me to observe this phenomenon. And finally, these adjustments to theoretical framework, analytical framework, and research methods combine to provide an additional theoretical contribution: they lead to the surprising finding that public organizations might play more than one active role in scientific instrumentality innovation. I describe three major organizational roles in this innovation system using the metaphors of “anchors” and two different kinds of “quartermasters”. After discussing the implications of my research for science policy and industrial policy, I conclude this dissertation by highlighting several opportunities for future research including further research into public innovation in goods and into scientific instrumentalities innovation, the need to revisit existing taxonomies of innovation, the opportunity for a services-dominant logic in innovation studies, the effects of new public management on the entrepreneurial state, opportunities to employ my methodological contributions, and the potential for revealing additional dark innovation using a comprehensive “diverse economies” framework (Gibson-Graham, 2008).

Chapter 2: Theoretical Framework

In the opening chapter, I introduced a gap in the literature related to public innovation in goods, the challenge of observing this dark innovation, and the potential for studying it in scientific instrumentality contexts. In this chapter, I will review the current state of knowledge regarding scientific instrumentality innovation while also unpacking the theoretical models that were used to establish this knowledge. I have already introduced the challenge of market bias in linear innovation models. I also briefly discussed the pros and cons of the chain-linked model of innovation and then introduced the potential advantages of using an innovation systems approach. Having already presented these arguments in a general form, my purpose in this chapter is to develop a richer understanding of existing theory and articulate a theoretical framework for this dissertation. To this end, I will provide a comprehensive examination of the existing literature on scientific instrumentality innovation and critically discuss the theoretical models underpinning it.

Over the course of this chapter, I will develop three theoretical propositions regarding the importance of public organizations to innovation in scientific instrumentalities. My discussion will follow the same chronology as the broader field of innovation studies—I begin with the aftermath of World War II and proceed through to recent research on innovation systems and university-industry interactive learning. The scientific instrument studies by von Hippel and his colleagues appear early on this timeline. They provide a basis for my first two theoretical propositions. Later in the chronology, the context of scientific instrumentalities disappears from the literature. Public research organizations (PROs) come to be positioned only as service providers—

their role is reduced to one that serves the needs of private companies. Although scientific instrumentalities are absent and PROs' roles are reduced to a market-orientation, I am able to draw insights from the more recent innovation systems literature and the related literature on university-industry/PRO-industry interaction. These insights provide the basis for my third proposition—a proposition that better connects scientific instrumentalities innovation with present-day innovation theory. But first, I must reach back and consider influential ideas from the 1940s because these laid the foundation for the early research on scientific instrumentalities.

"Linear" Developments

High-profile work of scientists during World War II—particularly the Manhattan Project—led to a "post-war paradigm" in innovation studies (Nemet, 2009). American engineer and science administrator Vannevar Bush articulated this paradigm in his argument that the knowledge created through public investments in science could radically advance the "frontiers" of medicine, industry, and national defense (1945a, 1945b). The idea that advancements in basic science were the antecedents to technological progress "held sway for 20 years or so" (B. Martin, 2010, p. 3) in acacdemic research and in public policy. During this time, the American consulting firm Booz Allen & Hamilton Inc. introduced similar thinking in its linear "new product development" process model (Booz Allen & Hamilton Inc., 1968; S. C. Johnson & Jones, 1957). Samuel Johnson of Johnson & Johnson and Conrad Jones of Booz Allen & Hamilton published an early six-step version of the model in *Harvard Business Review* in 1957 (S. C. Johnson & Jones, 1957). Several researchers adapted the specific steps and labels in various ways, maintaining the linear and sequential nature of the model (e.g., Cooper, 1994; Cooper & Kleinschmidt, 1986; Morley, 1968; Myers & Marquis, 1969; Rothwell, 1994). Along the way, a debate emerged about the directionality of the model. Those who ascribed to the 1940's post-war paradigm described an innovation process that was initiated and driven—or "pushed"—by advancements in applied scientific knowledge. In the 1950s and 1960s, an alternative hypothesis emerged suggesting that various forms of consumer and business demand served to "pull"—or determine the speed and direction of—innovation (Rosenberg, 1969; Schmookler, 1966). This demand-pull, linear, sequential innovation model was at the heart of Eric von Hippel's seminal work on scientific instrument innovation (von Hippel, 1976).

Von Hippel's paper "the dominant role of users in the scientific instrument innovation process" (1976) was his first academic publication and the starting point for his important concept of "user innovation" (Urban & Von Hippel, 1988; von Hippel, 1986, 1988). Bogers et al. (2010) argue that this seminal work was the first to notice that users can be innovators, and that it subsequently "set off a substantial amount of research investigating users as the sources of innovation" (p. 859). The research findings were reprinted in von Hippel's book, *The Sources of Innovation* (1988), which Fagerberg, Fosaas, and Sapprasert (2012) ranked as #13 on their list of top contributions to innovation studies. The 1976 and 1988 versions of this study are two of only four empirical studies that have focused on innovation in scientific instruments. Eric von Hippel was involved in all four publications (Riggs & von Hippel, 1994; Spital, 1979;

von Hippel, 1976, 1988)[7]. Because von Hippel has been a leading innovation scholar, it is important to understand these studies in the context of his career. Also, because this context is so understudied, it is important to closely examine the theory, method, and results of these studies. For these reasons, I dedicate the next several pages to the research.

We should begin with the first study (von Hippel, 1976, 1988). Here, von Hippel examined the development of 111 scientific instrument innovations in the United States, including four broad classes of scientific instruments: gas chromatographs, nuclear magnetic resonance spectrometers, ultraviolet spectrophotometers, and transmission electron microscopes.[8] He used the Myers and Marquis (1969) version of the linear innovation process; that is, the new product development process. He mapped the steps undertaken by scientists—which he referred to as “users”—versus the steps undertaken by scientific instrument manufacturing firms—which he referred to as “producers.” He found that in nearly all cases scientist-users performed all steps of the innovation process up to and including the development and use of pre-commercial prototypes. Only after this pre-commercial testing did producers in the private-sector acquire and begin to both commercialize and incrementally improve these instruments (see Figure 1).

[7] Although Spital (1979) does not discuss von Hippel’s involvement in his work, Spital is acknowledged as a research assistant in von Hippel’s (1975) draft working paper on scientific instruments and as an influential PhD student in von Hippel’s first (1988) book—the one that contained the final iteration of the original scientific instruments study.

[8] Note that von Hippel (1976) was studying instruments with broad applicability across scientific disciplines. All the instrument types he studied have applications in ocean science.

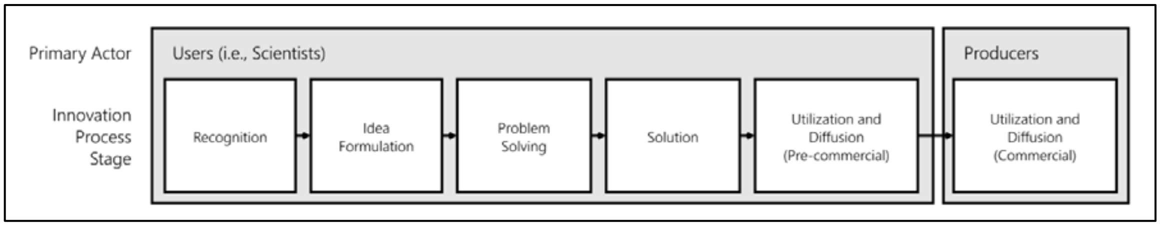

Figure 1. The primary actor in each innovation process stage in the scientific instrument innovation process (adapted from von Hippel, 1976).

Frank Spital, one of the research assistants on von Hippel's project (von Hippel, 1975, 1988), later extended the research (Spital, 1979). He added some nuance to the original observations, determining that scientist-users were responsible for "major improvement innovations" and many "minor improvement innovations" except those that were initiated by manufacturers in response to their competitors. Nearly 20 years later, William Riggs worked with von Hippel to revisit user innovation in the context of scientific instruments. Riggs and von Hippel (1994) reconfirmed the dominant role of users in scientific instrument innovation. They further suggested that user-driven scientific instrument innovations are more radical than producer-driven innovations which are more incremental.

To further develop his concept of user-innovation, von Hippel (1988) changed his research context from scientific instruments to "other, more 'normal' fields" (p. 20). I have previously suggested that this may have been subconscious blinkering—the context may have been seen as abnormal due to the "public" nature of scientific outputs and organizations. Over time, von Hippel's research program helped to dispel the myth that the "locus of innovation activity" (von Hippel, 1976) rests within manufacturing firms. He established that the "locus" of this activity can also rest in "users." To achieve this, von Hippel explored a range of research contexts (Urban & Von Hippel, 1988; von Hippel, 1986, 1988, 2005; von Hippel & Krogh, 2003). The context of scientific instruments provided an important theoretical contribution: the concept of user innovation. My work picks up where von Hippel and his colleagues left off; I return to this context and make important contributions with respect to public innovation.

As noted in the introductory chapter, it is likely that von Hippel and his colleagues were observing public innovation in goods. They noticed that scientists develop new scientific devices and, in Chapter 1, I noted that at the majority of their scientist users were likely employed by PROs. Remember that there is no mention of public organizations in the first three of these publications. There is only a passing reference to “universities” writ large (i.e., with no discussion of public/private distinctions) and “government laboratories” (Riggs & von Hippel, 1994, pp. 461-462). So, it is possible that I might be reading too much into this work. I have already conceded that not all scientists are publicly employed, but I have also drawn on the arguments of Perry and Rainey (1988) and O'Neil (1969) to show that most universities are public organizations. I argued that upwards of two-thirds of the organizations in the Riggs and von Hippel (1994) study may have been public. When I apply the Perry and Rainey (1988) distinction between public and private organizations to data on the organizations that employ scientist researchers in Nova Scotia, Canada (Statistics Canada, 2017), I find that 73% of scientists are employed by public organizations. And so, if von Hippel and his colleagues had been working in my regional context, a considerable portion of their scientist-users would have been employed by PROs. My point is that their conclusion regarding the "locus of innovation" for scientific instruments may have implications for public innovation in goods.

Because the evidence presented by von Hippel et al (Riggs & von Hippel, 1994; Spital, 1979; von Hippel, 1976, 1988) is so compelling, I accept that scientist users are the locus of innovation in scientific instrumentalities. However, their analysis rests on the assumption that innovation is a linear process and research in innovation studies has demonstrated this is not the case; innovation studies and has moved away from this assumption (B. Martin, 2013, 2016). The "state of the art" in innovation studies is now the innovation systems approach (Lundvall, 2013) and, as noted in Chapter 1, this approach is appropriate for studying public innovation because it does not default toward a market-orientation. I therefore propose that the conclusions drawn by von Hippel and his colleagues regarding the importance of "scientist-users" will apply to organizations that employ scientists—PROs—within systems of scientific instrumentality innovation. I propose to investigate whether or not:

> **Proposition 1: Public research organizations are the most important actors in a scientific instrumentality innovation system.**

"Chain-Linked" Processes

As I have noted, von Hippel (1988; 1976), Spital (1979), and Riggs (Riggs & von Hippel, 1994) provided the only empirical studies focused on scientific instrument innovation. While their work contributed in an important way to current research on user-innovation (e.g., von Hippel, 2005), the linear model that they used was replaced by new theoretical models, beginning with the chain-link model of innovation (Kline, 1985; Kline & Rosenberg, 1986).

In the 1950s and 1960s, the linear nature of innovation was mostly taken for granted. Debate focused on directionality: technology-push and demand-pull were seen as mutually exclusive hypotheses (Chidamber & Kon, 1994; Nemet, 2009). But by the 1980s, it was widely accepted that “innovation is neither smooth nor linear, nor often well-behaved” (Kline & Rosenberg, 1986, p. 285). Von Hippel and his colleagues foreshadowed the decline is use of linear models in two ways. First, they directly observed that some two-way—bidirectional—interaction existed at the point where pre-commercial instruments created by users were transformed into commercial instruments by producers (von Hippel, 1976). Second, they indirectly foreshadowed the fall of this model by selecting a context where scientists were operating at both ends of the linear flow: exerting both science-push and demand-pull. Von Hippel and his colleagues positioned their language on the “demand-pull” side of the debate. However, the “locus” of this demand rested in those individuals who were pushing the frontiers of science. This reality is evident, but not explicit, in their discussion. Later studies of scientific instrument innovation used different theoretical models and explicitly examined this “linked” nature of users and producers.

Stephen Kline and Nathan Rosenberg’s “chain-linked model” of innovation (Kline, 1985; Kline & Rosenberg, 1986) triggered a widespread shift away from linear models (B. Martin, 2013). Based on his 30 years of consulting to industry, Kline (1985) proposed a “linked-chain” model of innovation as an improvement to the “oversimple and inadequate” linear model (Kline, 1985, p. 36). In his model, Kline separated research activities which he defined as the processes that produce knowledge from the product development process which he labelled as “the chain-of-innovation” (Kline, 1985). He then argued that innovation involved not one sequential process, but five flows or pathways. These flows are illustrated in Figure 2, which is a simplified adaptation of several figures found in Kline (1985) and Kline and Rosenberg (1986).

The chain-linked model does not assume that innovation begins with research or with market demand. Instead, it highlights the ongoing interactions between research and development activities. The “chain-of-innovation” component of the model (paths labelled with a “1” in Figure 2) is like the linear product development model used by von Hippel (1976); it has has a market-orientation. However, feedback loops along this chain indicate that it is not one directional (paths labelled with a “2” in Figure 2). The addition of feedback loops alone makes the chain-linked model an improvement over linear models. But this is not the main point emphasized by Kline (1985) or Kline and Rosenberg (1986). In both papers, the authors emphasize the bi-directional linkages or pathways between research and development (paths 3, 4, and 5 in Figure 2).

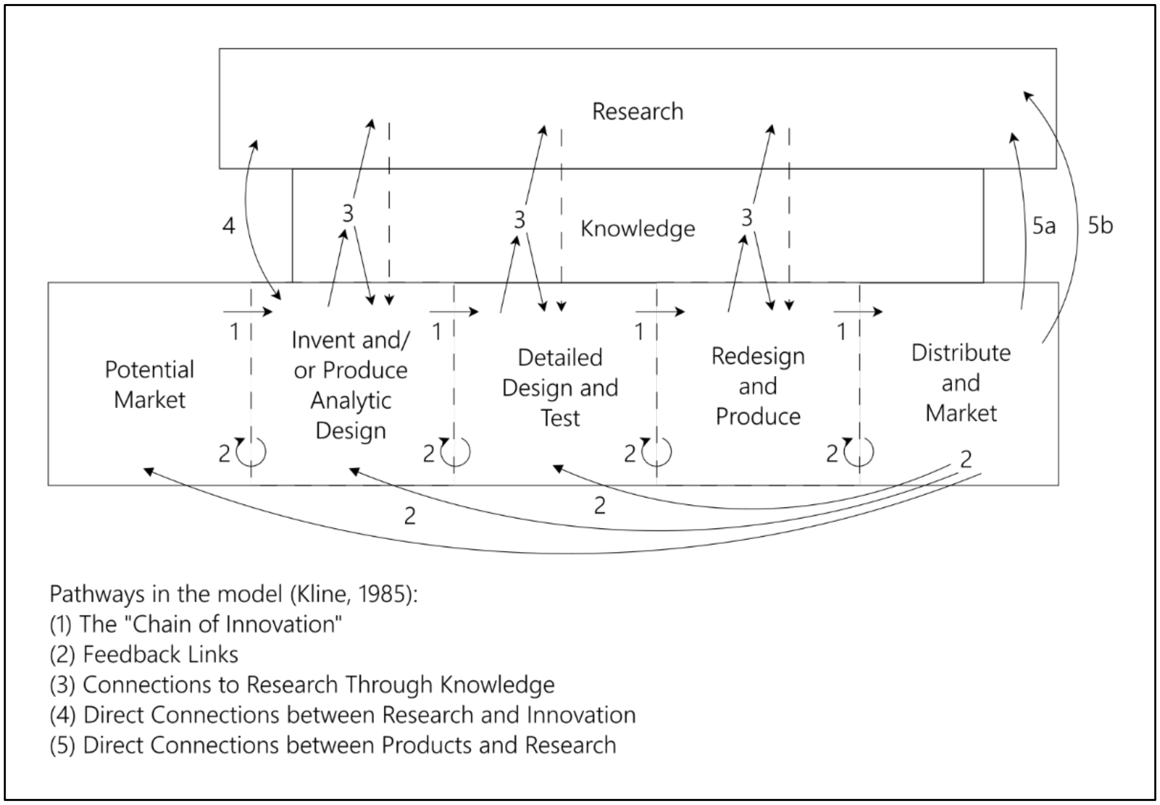

Figure 2. The chain-linked model of innovation (adapted from Kline, 1985; Kline and Rosenberg, 1986).

The chain-linked model includes three types of pathways between research and development, with the greatest emphasis placed upon the first type of pathway (those paths labelled with a “3” in Figure 2). In these pathways, “knowledge” serves as an intermediary between research and development activities. To establish this intermediary function, Kline (1985) analytically separates “science” into (A) research processes or activities (the top layer in Figure 2) and (B) the cumulative stocks of scientific knowledge (the middle layer in Figure 2). In his model, research activities contribute to, and rest upon, stocks of knowledge. These stocks of knowledge are also used by those who develop products. When either science or development activities find the knowledge stocks to be lacking, new research activities become triggered. Another way to explain the intermediary role of knowledge in this model is to think of it as “general information sources” (OECD, 2005): codified or tacit knowledge such as patent disclosures, journals, conference and meeting presentations, and informal networks or contacts. Kline (1985) and Kline and Rosenberg (1986) discuss these indirect pathways between research and development at length.

The chain-linked model also includes two types of *direct* pathways between research and development. Kline (1985) discusses these direct pathways at some depth in his original paper, but they receive “only brief discussion” in the more highly cited version of the model (Kline & Rosenberg, 1986, p. 293). Firstly, Kline (1985) identifies a direct and close-coupling between research and “invention.” He suggests that there are times when scientific research immediately stimulates invention, and times when nascent invention opportunities stimulate scientific research. He draws this direct linkage as a two-way arrow between research activities and invention activities (path “4” in Figure 2). Both papers note that this direct linkage relates to “invention” rather than “analytic design.” Kline uses the term “invention” in the same way as the U.S. Patent Office: “new design sufficiently different from prior art that it would not have been obvious beforehand to an individual skilled in the relevant art” (Kline, 1985, p. 37). Meanwhile, he describes “analytic design” as an engineering process that selects from, and improves upon, existing known designs. Kline and Rosenberg (1986) note that this distinction makes “invention” a “significant departure from past practice” (Kline and Rosenberg 1986, p. 292). They therefore explain that their first direct linkage between research and development results in radical innovations, such as “semiconductors, lasers, atom bombs, and genetic engineering” (Kline and Rosenberg, 1986, p. 293).

Kline and Rosenberg (1986) describe the second type of direct linkage between research and development as “the feedback from innovation, or more precisely from the products of innovations, to science” (p. 293). In his illustrations, Kline (1985) includes two one-way arrows pointing from the end of his innovation process to research activities (see the pathways labeled with a “5” in Figure 2). One of these arrows represents the way that new products initiate new science. For example, the introduction of combustion engines leading to research on engine performance problems illustrates this process. Kline (1985) calls the other arrow “support for science.” He uses de Solla Price’s (1984) scientific instrumentalities concept, and explains it in this way: “the production of new instruments, tools, and processes has in many instances made possible new forms of research” (Kline 1985, p. 41). Both papers anecdotally point to the development of the telescope and Galileo’s subsequent advancements in astronomy, as well as the development of the microscope and Pasteur’s subsequent advancements in micro-biology (Kline, 1985; Kline & Rosenberg, 1986). So, based on anecdote and extant theory, the chain-link model recognizes the important flow of new instruments and techniques into science.

Kline’s (1985) direct pathways between research and development are theoretically grounded in Rosenberg’s earlier assertion that “science is not entirely exogenous” (Rosenberg, 1982). In other words, the chain link model does not consider science to be outside the market. Instead, it considers scientific research and technological development to be directly and indirectly linked. The direct links between research and development are most relevant to this dissertation. To further understand the nature of these links, I turn to theory from science and technology studies (STS). STS generally uses a different approach to articulating theory. The boxes and lines discussed thus far in relation to the linear and chain-linked models will give way to concepts and metaphors. We will see that STS scholars describe the same "direct links" (Kline, 1985; Kline & Rosenberg, 1986) between science and technology as "symbiotic" relations (de Solla Price, 1984; Gorm Hansen, 2011; Rosenberg, 1992).

"Symbiotic" Relations

Derek de Solla Price was one of the world's foremost historians and sociologists of science. Submitted only months before his sudden death, de Solla Price's (1984) paper on "the science/technology relationship" provides a macro-level description of innovation in scientific instrumentalities. Drawing on examples from history, de Solla Price discusses the important relationships among those who perform science and those who craft scientific techniques. For him, it was important to separate the processes of science from the products of science. The products, or outputs, of science can be described as scientific *know-what.* The ancient Greeks called these products of science *epistêmê*, which means understandings and beliefs. As noted earlier, de Solla Price (1984) used the term "scientific instrumentalities" to describe the *know-how* of science: the processes, craft, or what the Greeks called *technê*. As I noted in Chapter 1, "instrumentalities" includes both instruments and techniques. An instrumentality can be any "laboratory method for doing something to nature or to the data at hand" (de Solla Price, 1984). De Solla Price (1984) asserts that instrumentalities "are clearly technology, an understanding of the way to do things" (p. 13). However, this technological knowledge may or may not be embedded in scientific equipment or machinery.

This theoretical approach signifies a departure from the "scientific instruments" studied by von Hippel and his colleagues (Riggs and von Hippel, 1994; Spital, 1979; von Hippel, 1976; von Hippel, 1988); they only studied innovations that were embedded in scientific machinery and equipment. I have discussed the importance of considering all forms of product innovation: goods as well as services. And it is important to revisit this point now because it allows me to expand on the kinds of private companies that might be involved in scientific instrumentality innovation. It is important to understand the different organizations involved in scientific instrument innovation versus scientific instrumentality innovation.

Von Hippel and his colleagues did not consider the possibility that private companies might produce what they called "technique-only" (Riggs & von Hippel, 1994, p. 461) innovations—innovations that are not embedded in machinery or equipment. Riggs and von Hippel (1994) explained that they considered technique-only innovations to be the exclusive domain of scientists. They assumed that techniques had "low commercial importance" because they could not be manufactured (Riggs and von Hippel, 1994, p. 461). However, this runs counter to insights from the innovation-in-services literature (Barras, 1986; Gallouj, 2002; Gallouj & Weinstein, 1997): technique-only innovations are regularly appropriated by private companies as "knowledge intensive business services" (Miles et al., 1995). Services can have high commercial importance. It would therefore be surprising not to find companies that deliver knowledge intensive research services. Because de Solla Price (1984) includes both equipment and techniques in his concept of “scientific instrumentalities,” his research makes it possible to expand beyond scientific instrument manufacturing and also consider scientific service delivery.

Note that despite his broader theoretical framework, de Solla Price comes to the same conclusion as von Hippel (1976): scientists are the “locus of instrumentality innovation” (de Solla Price, 1984). And like Riggs and von Hippel (1994), de Solla Price (1984) notes the radical nature of scientific instrumentality innovations. In fact, he claims that scientific instrumentalities are the most radical of all innovations (de Solla Price, 1984). Using several historical examples, he explains that novelty is high because “the inventions of instrumentalities are precisely those that defy reasonable attempts to make a technology assessment” (de Solla Price 1984, p. 13). The novelty of scientific instrumentality innovations means that they not only drive scientific progress, but they also have disproportionate impact on innovation outside of science. This is because scientific instrumentality innovations are often “general purpose” or broadly applicable across fields. Stated differently, instrumentality innovations “move very often from being tools of the laboratory to a much wider commercial application” (de Solla Price, 1984, p. 14). De Solla Price therefore develops an argument that, “the scientific instrument industry […] exercises a leverage on innovation and scientific advance out of all proportion to its relatively modest size in economics and manpower” (1984, pp. 19-20). This suggests that scientific instrumentalities are the most important innovation context.

Rosenberg (1992) also notes the importance of scientific instrumentality innovation. He suggests that the primary product of basic science is knowledge about the nature of our universe. New instrumentation techniques are an important and overlooked by-product of this work (Rosenberg, 1992) because they often provide “an ability to observe or measure phenomena that were previously not observable or measurable at all" (Rosenberg 1992, p. 382). Like de Solla Price, Rosenberg (1992) draws upon histories of scientific instrument innovation, including computing, magnetic resonance imaging, electron microscopy, and lasers. He uses these examples to discuss the movement of instrument innovations across scientific disciplines and through various industries:

> Improved instrumentation has had consequences far beyond those that are indicated by thinking of them simply as an expanding class of devices that are useful for observation and measurement […] they have played much more pervasive, if less visible roles, which included a direct effect upon industrial capabilities, on the one hand, and the stimulation of more scientific research on the other. (Rosenberg, 1992, p. 388)

Here Rosenberg has echoes the sentiment that scientific instrumentalities are a highly important innovation context due to their wide diffusion through society. This diffusion is at least partly thanks to the work of private industry. Like others (Riggs and von Hippel, 1994; Spital, 1979; von Hippel, 1976; von Hippel 1988), Rosenberg (1992) notes that private sector manufacturers make incremental improvements to scientific instruments. These improvements in performance, versatility, price, and usability for those with less training in the original applications of the technology, help to facilitate diffusion of the innovations. But further to collaboration with Kline (1986), Rosenberg (1992) reminds his readers that innovation is not linear. A new scientific instrumentality can stimulate follow-on research with respect to performance, materials, or ancillary technologies, as well as open new fields of research, be adapted to other fields of research, and be adapted to commercial applications (Rosenberg, 1992).

De Solla Price (1984) and Rosenberg (1992) agree on the widespread importance of scientific process innovations as well as the nature of the relationships between scientists and the scientific instrumentality industry. They both reject the idea that knowledge flows one-way from science to industry via instruments or any other means. It is appropriate to think of scientific instruments as the inputs or “capital goods of the scientific research industry” (Rosenberg 1992, p. 381), yet it is also important to recognize that, “scientific instrument firms are quite often spin-offs from great national facilities in experimental science […and…] the mechanism for the entrepreneuring and expansion of such crucial high technology laboratories has been government procurement” (de Solla Price, 1984 p. 18). And so, the relationship between PROs and private instrumentality companies can be described as “interactive” (Rosenberg, 1982, p. 158), “dialectical” (Rosenberg, 1982, p. 158), “complementary” (Rosenberg, 1992, p. 386), or “symbiotic” (Rosenberg, 1992, p. 386). The PROs are primarily but not exclusively populated with scientists, while the private companies are primarily but not exclusively populated with engineers/technicians. Together, these constitute one community:

> Scientists and engineers seem to be bound together in their invisible colleges, not so much by any communality of their paradigms, ways of thought, and cognitive training, as by a guild-like communality of the tools and instruments that they use in their work. (de Solla Price, 1984, p. 15)

In other words, communities of scientists and technicians are united by shared expertise in particular scientific instrumentalities.

De Solla Price (1984) and Rosenberg (1992) both present scientific instrumentalities as collaborations between science and industry. They describe the collaboration as complex, bidirectional, and focused on scientific know-how, “instrumentalities,” or *technê,* as discussed above. This collaboration remains unexplored in the linear studies of scientific instrument innovation (Riggs and von Hippel, 1994; Spital, 1979; von Hippel, 1976; von Hippel, 1988). Riggs and von Hippel note that there is some two-way information transfer “and occasionally more substantial interaction between users and manufacturers” (1994 p. 468). But in their words, “our focus on ‘the’ source of innovation… has given short shrift to patterns of joint user-manufacturer involvement in the innovation process” (Riggs and von Hippel, 1994 p. 468). By stepping back and considering the long-history of innovation in scientific instrumentalities, de Solla Price (1984) and Rosenberg (1992) come to a different conclusion. According to Rosenberg, “the migration of scientific instruments to industry has been matched by a reverse flow of fabrication and design skills that have vastly expanded the capacity of university scientists to conduct research” (1992, 386). From this perspective, I would argue that PROs exist in a symbiotic relationship with private scientific instrumentality companies.

Brigitte Gorm Hansen (2011) describes a similar symbiosis between a Danish university biology lab and a co-located biotech company. Gorm Hansen explains that the company is more than a simple linear commercialization or spin-off from the laboratory’s work, although this is part of the story. The company is also a partner in funding applications, a means of acquiring instrumentation that the university cannot afford, and a provider of knowledge-intensive research services for the lab. Gorm Hansen argues that the biotech company makes the PRO more competitive in its field by “sequestering” activities that might otherwise be “toxic” to highly productive science:

> By having an in-house biotech company, the academic scientists will not have to go through the laborious process of high-throughput screening, enzyme production, or other routine tasks. These tasks are not external to science, they are as necessary as breathing. (Gorm Hansen, 2011 p. 500)

In this way, Gorm Hansen describes a research laboratory and a biotech company that have co-evolved through a symbiotic relationship of mutual benefit: the PRO becomes better at producing science—*epistêmê*—and the company becomes better at producing technology, or *technê*. In general terms, this partnership consists of a private company that contributes scientific process innovations—instrumentality services—and a PRO that contributes scientific product innovations—scientific insights. Gorm Hansen speaks of these two organizations' "mutual dependence" in the same ways that de Solla Price (1984) and Rosenberg (1992) speak of the broader interdependence between science and scientific instrumentalities. The symbiotic relationship noted by these STS scholars can be further understood in terms of "interactive learning" (Lundvall, 1988), thereby drawing upon insights from the innovation systems literature.

Interactive Learning

Pioneered by Christopher Freeman (1987), Bengt-Åke Lundvall (1988), and Richard Nelson (1993), the innovation systems approach focuses on the "interactive learning" (Lundvall, 1988) that occurs among many different actors withinin a particular institutional environment. Freeman (1987) published the first work in this area, explaining how unique institutional arrangements, such as industrial groups or keiretsu, developed into an effective "national innovation system" (NIS) for post-war Japan. At the same time, Lundvall was writing a book chapter (Lundvall 1988) that established the theoretical basis upon which to view innovation as "an interactive process involving many actors and extending over time" (Lundvall, 2013, p. 33). To further this nascent national innovation system approach, Richard Nelson then edited a volume comparing various national innovation systems (Nelson, 1993). These publications introduced the concept of an innovation system which researchers describe as an important advancement over prior linear and chain-linked approaches to studying innovation (Caraça et al., 2009; Fagerberg et al., 2013).

The innovation systems approach has since been adapted from a focus on national systems to sub-national or “regional innovation systems” (RIS) (Asheim & Isaksen, 2002; Asheim et al., 2011) and to “sectoral” systems (see Malerba, 2005). Some Canadian geographers might object to my use of the innovation systems approach—which is predominantly used by European scholars. Yes, the economic geography of Canada is different than many countries of Europe, however I would argue that the innovation systems approach has proven to be highly adaptable across geographic contexts. It has been amendable to research on innovation in such disparate contexts as Japan (C. W. Freeman, 1987), Mexico (De Fuentes & Dutrénit, 2012; De Fuentes & Dutrénit, 2016), and Canada (Doloreux, 2003; Niosi, 2000; Niosi & Zhegu, 2010). I agree with Holbrook and Wolfe (2000) that a regional innovation systems approach is most suitable to Canada, and that it is more suitable than a clusters approach—which presumes a greater degree of agglomeration than is found in many Canadian regions. Further, some innovation scholars might now ask why I have not used another competing approach: the triple helix framework (Etzkowitz & Leydesdorff, 1997). Although scholars who use this approach sometimes recognize hybrid entities (Etzkowitz, 2002), they begin their work by theoretically framing government, academia, and industry as different elements of a system. To achieve the purposes of this dissertation, I must use a theoretical framework that does not presume differences between public and private organizations.

Charles Edquist (1997) argues that an innovation system can be defined as any collection of organizations and institutions—i.e., the rules that shape organizational interaction (see Glossary and further discussion of organizations and institutions in Chapter 4). He suggests that early research on innovation systems intentionally left the conceptual boundaries vague. This flexibility is part of what makes the innovation systems approach such a valuable theoretical tool. Many different overlapping boundaries can be drawn around a system:

> …innovation systems may be supranational, national or subnational (regional, local) – and at the same time they may be sectoral within any of these geographic demarcations. There are many possible permutations. Whether a system of innovation should be spatially or sectorally delimited depends on the object of study. (Edquist, 1997, p. 12)

To use the innovation systems concept, one must be able to identify such boundaries, as porous as they may be. Only the most exceptional cases are closed off from the outside world (Edquist, 2001). In this way, the innovation systems approach imposes a system-level theoretical framework but provides considerable flexibility in defining the system boundaries.

Within the boundaries of an innovation system, the innovation systems approach focuses attention on a particular phenomenon. Lundvall (1992) describes the innovation systems approach as a “focusing device”—a kind of social scientific theory—that places our attention on processes of “interactive learning.” This emphasis arises from an underlying assumption that “the most fundamental resource in the modern economy is knowledge, and, accordingly, that the most important process is learning” (Lundvall, 1992, p. 1). Note that Lundvall’s “focusing device” does not point toward the noun *knowledge,* or any a static outcome. Instead, Lundvall’s (1988; 1992) earliest contribution to the innovation systems approach was to embed an understanding of innovation as a verb: an ongoing, ubiquitous, and cumulative learning process. Meeus and Oerlemans (2005b) explain that, in the context of the literature on innovation systems, learning is “a process in which all kinds of knowledge are (re-) combined to form something new” (p. 159). The concept of interactive learning focuses on understanding the learning processes that take place between actors in an innovation system, not merely identifying the presence or absence of such interactions.

The interactive learning concept was empirically grounded in Lundvall’s research on user-producer interactions (1988). Lundvall (1988) argues that innovations emerge from “organized markets” of user and producer relationships, as opposed to “free markets.” He argues that the producers of product innovations have several incentives to establish close relationships with their users, including: (1) the opportunity to appropriate further process innovations developed by users or to understand the competitive nature of these process innovations; (2) the ability to understand new user demands; (3) access to tacit knowledge developed through the use of their products; (4) an understanding of their products’ relationships with other products, referred to as “bottlenecks and interdependencies”; and (5) an understanding of users’ capabilities with respect to potential new products (Lundvall, 1988). Lundvall (1988) also argues that users have similar incentives to maintain close relationships with producers, including the value they gain from knowledge about the potential use-value of new products and knowledge about the competencies, reliability, and trustworthiness of different producers with whom they might cooperate to develop new products/uses. These various incentives are particularly strong for the development of “complex and specialized equipment” (Lundvall 1988) and this encourages “direct cooperation” between users and producers (Lundvall, 1988). But even if users and producers are not cooperating directly, Lundvall suggests that they are subject to “systemic interdependence” (Lundvall, 1988, p. 350). In other words, the innovation actors in a “system” are always learning from other actors in a somewhat-organized fashion. The degree of interdependence may be greater in contexts with stronger incentives for interactive learning. This is the way that de Solla Price (1984) and Rosenberg (1992) describe interactions in the field of scientific instrumentalities. Given the foregoing, I would argue that scientific instrumentalities likely involve a particularly strong form of interactive learning.

Science-Industry Interaction

In Chapter 1, I explained that the innovation systems approach has yet to be applied to the context of scientific instrumentalities. There is a large body of literature on interactive learning between science and industry, including university-industry (U-I) and PRO-industry (PRO-I) interaction. However, this literature spans many sectors of the economy and does not include a focus on scientific instrumentalities. An extensive review of this literature is provided by Perkmann et al. (2013). In this body of work, science is represented broadly by PROs, including universities and government laboratories. “Science” also takes place in private laboratories, but that is commonly referred to as R&D in this literature. Overall, the roles of PROs and private companies are sharply differentiated: PROs produce knowledge, and private companies produce innovation. As a result, the science-industry interaction literature has a limited view of PRO innovation roles; PROs are called upon to interact with private sector knowledge users and transfer technology to the market (Perkmann et al., 2013). I consider this view to be overly restrictive since there are many other ways PROs might engage in interactive learning. In this section, I review the literature for ways that PROs engage in interactive learning and I then develop a channels of interactive learning framework for use in this dissertation. Most recent analyses of science-industry interaction investigate a single channel of interactive learning between science and industry, such as co-patenting or scientific co-authorship (see Appendix A for a summary of 22 recent publications, 2017-2018). I join several scholars who have recently investigated science-industry interaction across multiple channels (e.g., Arza & Carattoli, 2017; Calignano & Fitjar, 2017; Calignano, Fitjar, & Kogler, 2018; Martin & Rypestøl, 2017) and some who have integrated multiple channels into a single analysis (e.g., Xu, Wu, Minshall, & Zhou, 2017).

Interaction between PROs and private industry can take a variety of forms. Many different types of interactive learning are discussed in studies of U-I and PRO-I interaction. Indeed, two important subfields of study—academic entrepreneurship and academic engagement—differ in part because they emphasize different types of interactive learning. The literature on academic entrepreneurship focuses on three types of commercialization activities undertaken by universities: patenting and licensing, incubation of spin-off companies, and various kinds of university-industry research collaborations (Geuna & Muscio, 2009; Larsen, 2011; Rothaermel, Agung, & Jiang, 2007). Closely related to academic entrepreneurship is the concept of academic engagement, which Perkmann et al. (2013) define as an informal type of technology transfer: "knowledge-related collaboration by academic researchers with non-academic organizations" (Perkmann et al., 2013, p. 424). Following this definition, Perkmann et al. (2013) identified and reviewed 36 publications on academic engagement. Twelve of these studies included data on various types of academic-industry interaction, and this is summarized in Table 1. In order of frequency, the most commonly identified interactions appearing in at least six of the 12 studies were: consultancy, (co)patenting or patent assignment, movement of human resources—particularly students, co-attendance/presentation at conferences, (co)publications, joint R&D, licensing of intellectual property, and the creation of spin-off companies (see Table 1). Missing from the analysis by Perkmann et al. (2013) is work by Claudia De Fuentes and Gabriela Dutrénit (2012) to identify the “best channels of academia-industry interaction” in Mexico. I have added De Fuentes and Détrunit’s (2012) paper to the list in Table 1 because it adds important elements that the other research overlooks. First, it considers the “mutual benefits” that arise for both science and industry. Most studies focus only on benefits for the private sector. Furthermore, the De Fuentes and Dutrénit (2012) typology is the most comprehensive of all those identified in Table 1: it covers the widest range of interaction channels.

De Fuentes and Dutrénit (2012) identify four primary “channels” of interactive learning that can be found between PROs and industry. They delineate an information and training channel, an R&D projects and consultancy channel, an intellectual property rights channel, and a human resources channel (De Fuentes and Dutrénit, 2012). Within these channels, they identify 10 forms of interaction (see Table 1). As a result of their empirical work in Mexico, they found that all channels of interaction produce benefits for academia and industry, but certain channels such as joint or contract R&D, property rights, and human resources, provide better long-term benefits to industry.

Table 1

Types of Science–Industry Relationships in the Academic Engagement Literature

	Publications	Conferences	Informal Information	Training	Contract R&D	Joint R&D	Consultancy	Licensing	Patenting	Commercial iz-ation	Spin-offs	Donation / Sponsorship	Movement of HR (incl.	Shared Personnel	Other
Bekkers and Freitas (2008)	✓		✓	-	✓			✓	✓	-	-	-	✓[1]	-	Alumni & Professional Associations; “Organized Activities”
Boardman (2008)	✓[2]		-	-	-	-	✓	✓	✓[3]	✓	-	-	✓[1]	-	
Boardman and Ponomariov (2009)	✓[2]		✓	-	-	-	✓	✓	✓[3]	-	-	-	✓[4]	✓	“Formal contact”
De Fuentes and Dutrénit (2012)	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	-	-	✓	-	
D’Este and Patel (2007)	-	✓	-	✓	✓	✓	✓	-	-	-	✓	✓[5]	-	-	
Giuliani et al. (2010)	-	✓	✓	✓	✓	✓	✓	-	-	-	✓	-	✓[4]	-	“Mailing lists”
Grimpe and Fier (2010)	✓[2]		-	-	-	-	✓	-	-	✓	-	-	-	-	

	Publications	Conferences	Informal Information	Training	Contract R&D	Joint R&D	Consultancy	Licensing	Patenting	Commercial iz-ation	Spin-offs	Donation / Sponsorship	Movement of HR (incl.	Shared Personnel	Other
Gulbrandsen and Smeby (2005)	-	-	-	-	-	-	✓	-	✓	✓	✓	-	-	-	
Haeussler and Colyvas (2011)	-	-	-	-	-	-	✓	-	✓	-	✓[6]	-	-	-	
Klofsten and Jones-Evans (2000)	-	-	-	✓	✓	✓	✓	✓	✓	✓[7]	✓	-	-	-	“Testing”
Martinelli et al. (2008)	-	-	✓	-	✓	✓	✓	-	✓	✓	-	✓	✓[4]	-	
Nilsson et al. (2010)	✓	✓	✓	-	-	-	-	✓	✓	-	✓	✓	✓[8]	✓	
Walsh et al. (2008)	✓[2]	-	-	-	-	✓	✓	✓	✓	-	✓	✓	✓[8]	✓	“Study group”
Frequency (out of 13 studies)	7	8	6	4	6	7	12	7	10	5	7	4	8	3	

Notes. [1]Includes two separate forms of HR interaction: students being hired by industry, and general employee mobility. [2]Specifies “coauthored” publications and/or conference presentations. [3]Also includes copyright. [4]Specifies only student mobility. [5]Specifies industry funding of PRO laboratories/equipment. [6]Specifically studied whether or not an academic had “founded a company”. [7]This category was labelled “sales” in the paper, but has been coded as “commercialization” in this table because of the description provided: “Commercial selling of products developed within the university” (Klofsten and Jones-Evans 2000). [8]Includes a general category for employee mobility that does not explicitly include students.

Four types of interaction are identified elsewhere in the literature. Two of these types of interaction would help to expand the De Fuentes and Dutrénit (2012) model. First, donation or sponsorship-based R&D (D'Este & Patel, 2007; Martinelli, Meyer, & Von Tunzelmann, 2008; Nilsson, Rickne, & Bengtsson, 2010; Walsh, Baba, Goto, & Yasaki, 2008) can be included as a type of formal R&D interaction alongside contract R&D and joint R&D (see Table 1). Second, "shared personnel" is a type of human resource interaction where company founders or employees are concurrently employed by a PRO (Boardman & Ponomariov, 2009; Nilsson et al., 2010; Walsh et al., 2008). There are two types of interaction mentioned elsewhere in the literature—"spin-offs" and "commercialization." However, I do not see these as appropriate additions to the De Fuentes and Dutrénit (2012) model.

A "spin-off" is a commonly identified type of academic entrepreneurship / engagement (D'Este & Patel, 2007; Giuliani, Morrison, Pietrobelli, & Rabellotti, 2010; Gulbrandsen & Smeby, 2005; Haeussler & Colyvas, 2011; Klofsten & Jones-Evans, 2000; Nilsson et al., 2010; Walsh et al., 2008). However, "spin-off" is more appropriately used to describe a type of company, or the process of creating a company from academic research. Spin-off is therefore short-hand for a combination of academia-industry interactions that take place when a company is founded. The idea of a spin-off can capture patenting, licensing, and the movement of human resources. Since those interactions are already accounted for in the De Fuentes and Dutrénit (2012) model, the addition of a spin-off channel is purely repetitive. Similarly, "commercialization" is a commonly identified type of academic entrepreneurship (Boardman, 2008; Grimpe & Fier, 2010; Gulbrandsen & Smeby, 2005; Klofsten & Jones-Evans, 2000; Martinelli et al., 2008); it is used to describe a collection of academia-industry interactions such as patenting, licensing, and joint or contract R&D. The types of interactions that are included under the label “commercialization” can vary (Boardman, 2008; Grimpe and Fier, 2010; Gulbrandsen and Smeby, 2005; Klofsten and Jones-Evans, 2000; Martinelli et al., 2008), but all are included in the De Fuentes and Dutrénit (2012) typology.

Given the discussion above, I present an expanded set of possible interactions in Figure 3 and Table 2. Notice that I have not labelled elements of Figure 3 with the terms “science” and “industry” (or PRO-I, or U-I). Instead, my adaptation allows for any type of interactive learning to occur between any types of organizations—public or private. This helps to avoid biasing the interactions in favour of private sector learning. The typology is adapted from De Fuentes and Dutrénit (2012) and includes the addition of a fifth channel: the capital equipment and technical services channel. My adapted typology is represented as horizontal lines in Figure 3 and described in the rows of Table 2. Where their original framework identified seven types of interaction within four channels, my adaptation includes seven types across five channels (See Table 2). I achieved parsimony by only dividing a channel of interaction into multiple sub-categories where absolutely necessary—to differentiate between the movement versus sharing of human resources and between formal versus informal information exchanges. The result is a simple yet comprehensive channels of interactive learning framework that does not assume PROs are outside the market, or that they do not drive their own benefits from interactive learning.

Figure 3. Channels of interactive learning framework. Adapted from De Fuentes and Dutrénit (2012).

Table 2

Five Channels of Interaction and Seven Types of Interactive Learning Relationships

Interaction Channel	**Types of Relationships**	**Knowledge Flows**
R&D Projects & Consultancy Channel	Formal research or development contracts, partnerships, or sponsorships.	Bidirectional
Intellectual Property Rights Channel	Licensing or transfer of intellectual property	Directed
Human Resources Channel	Mobility of human resources (i.e., hiring employees from another organization -- incl. education/training organizations -- or losing employees to another organization).	Directed
	Sharing employees or decision-makers (i.e., key shareholders / directors) with another organization, including visiting or employee loan models.	Bi-directional
Information and Training Channel	Formal sharing of information (e.g. through joint training, co-authorship, etc.)	Bidirectional
	Regular informal relationships among key employees	Bidirectional
Capital Equipment and Technical Services Channel	Provision/acquisition of capital equipment or technical services—may be a financial or in-kind transaction.	Directed

Note. Adapted from De Fuentes and Dutrénit (2012).

Although interactive learning is the theoretical focus for this dissertation, I should note that the literature on science-industry interaction discusses several other innovation factors. There is particular emphasis on the absorptive capacities of learning partners (Cohen & Levinthal, 1990; De Fuentes, 2009; Gilsing, Nooteboom, Vanhaverbeke, Duysters, & van den Oord, 2008; Giuliani, 2005), and debate about the role of geographic proximity/distance in interorganizational learning (De Fuentes & Dutrénit, 2016; R. Martin & Moodysson, 2011a). To maintain my theoretical focus, I treat distance and absorptive capacity as control variables when I develop my analytical approach in Chapter 4.

Now that I have developed an interactive learning framework, I can use it to consider the nature of interactive learning for scientific instrumentalities. In the previous section, I reviewed theory from STS which points to "symbiosis" between PROs and the scientific instrumentality industry (i.e., de Solla Price, 1984; Gorm Hansen, 2011; Rosenberg, 1992). Like "commercialization" and "spin-off," I treat "symbiosis" as a label for particular combination of interactive learning channels. Symbiosis implies mutual interdependence; in terms of interactive learning it implies a relationship involving multiple types of interaction with learning benefits for both parties. Thus, if relationships between PROs and scientific instrumentality companies are likely to be symbiotic, then they are likely to involve multiple simultaneous channels of interactive learning with knowledge flowing in both directions. I therefore propose that:

> **Proposition 2: The interactive learning between PROs and scientific instrumentality companies involves multiple channels and is bidirectional.**

In other words, the relationships between PROs and scientific instrumentality companies are not one-way and one-dimensional. They should not be reduced to a linear push or pull. Instead, these relationships include multiple types of interaction with knowledge flows in both directions.

The particular mix of interaction types may vary from one scientific instrumentality relationship to the next. However, the literature has provided several clues to the channels that are likely the most important and I can use these to develop a third proposition. The work of von Hippel and his colleagues (Riggs and von Hippel, 1994; Spital, 1979; von Hippel, 1976; von Hippel, 1988) suggests that flows of formal intellectual property from PROs to scientific instrumentality companies —including explicit designs or prototypes of scientific process innovations—should be important to this context. These intellectual property flows might include co-patenting or licensing, but as noted in those studies, IP flows would tend to occur infrequently—only as the last step in a linear process for some new scientific instruments. de Solla Price (1984) notes that the norms of open scientific publication conflict with the choice to apply for patent protection on a new scientific instrumentality. Furthermore, the work of Kline and Rosenberg (1986) and Rosenberg (1992) does not discuss formal IP flows but is focused on interactions involving capital equipment. The work of Gorm Hansen (2011) adds that some private companies provide scientific technical services as part of their symbiotic relations with PROs. The capital equipment and technical services channel is therefore particularly important for interactive learning in scientific instrumentalities.

Note that customer-supplier relations do not appear in any of the 13 academia-industry interaction typologies in Table 1. PROs are not seen as customers in these typologies because they are outside of the market. However, flows of capital equipment are normally included in discussions of interactive learning (Lundvall, 1988): product innovations in one industry become process innovations in another. Increasingly, the flows of knowledge-intensive business services are also emphasized (Doloreux, Freel, & Shearmur, 2010; Miles et al., 1995). Even though these types of interaction might not normally be important to studies of academia-industry interaction, the technical knowledge transferred from industry to PROs appears to be an important interaction in the field of scientific instrumentalities; it is explicitly identified in the chain-linked model (Kline, 1985; Kline and Rosenberg, 1986) and it is central to the work of de Solla Price (1984) and Rosenberg (1992). I therefore propose that:

> **Proposition 3: The most important interactive learning channels for scientific instrumentality innovation involve the provision and acquisition of capital equipment and technical services.**

In other words, the theory suggests that customer-supplier relationships are central to interactive learning processes in a scientific instrumentalities innovation system.

Summary of the Theoretical Framework

The purpose of this chapter is to examine existing theory with respect to scientific instrumentality innovation and, at the same time, develop a theoretical framework that does not default toward a market-orientation. I present the existing literature as a chronology:[9] beginning with the post-war linear model and progressing to present-day discussions of science-industry interaction. Near the beginning of this chronology I review empirical studies focused on scientific instrument innovation. These use an inappropriate linear model but still provide rich empirical observations. In the middle of the chronology, I present the work of several scholars who did not make direct empirical observations, but nonetheless developed rich theory from anecdotal and historiographic discussion of scientific instrumentalities. These mid-points along my chronology

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[9] There is a potential drawback to plotting this chapter along a timeline. I have written a progressive and teleological account, but my intent is not to suggest that "old" ideas have disappeared. Readers should not assume that ideas falling early on my timeline are now gone. For example, the linear model is still evident today (Godin, 2006, 2017).

theoretically frame the science-technology relationship as “linked” or “symbiotic.” Then, near the end of the chronology, I present the flexible theory that is used to study innovation today—the innovation systems approach and channels of interaction frameworks. I emphasize the benefits of focusing on innovation as an interactive learning process. I also emphasize the need to consider mutual benefits from science-industry interactive learning, not only benefits for the private market. This led me to develop a channels of interactive learning framework that allows PROs to fully engage in interactive learning.

My resulting theoretical framework is composed of three parts which serve as the theoretical basis for my work in the coming chapters. First, I have framed innovation as an interactive learning process. Working from this concept, I follow an innovation systems approach that does not privilege the free market. I further develop the innovation systems approach as part of my analytical framework in Chapter 4—where I engage with questions about how to define innovation system boundaries and how to observe interactive learning processes. For now, I have focused on the *epistêmê*—the know-what—of the innovation systems approach. I have used the concept of interactive learning to build a channels of interaction typology that does not presume one-way flows from PROs to private companies. This is the second element of my framework. The first two elements work together to provide this dissertation with a theoretical lens that focuses my work on a particular conceptualization of innovation. The third element of my framework is the set of propositions developed in this chapter. These are my own ideas about the importance of public organizations for scientific instrumentality innovation. They are based on prior research but are yet to be empirically tested. I will use the theoretical lens as I proceed to empirically investigate these propositions later in the dissertation. This theoretical framing also provides the basis for a fourth proposition that will emerge from a discussion of research context in the following chapter.

Chapter 3: Research Context

Thus far, I have identified scientific instrumentalities as a field where one might reasonably expect to observe public innovation in goods and services. I have also reviewed prior research regarding scientific instrumentality innovation and developed a theoretical framework that focuses on innovation as an interactive learning process involving all kinds of organizations—public and private. In this chapter I will use this theoretical framework to describe the specific empirical context used in this dissertation: the field of ocean science instrumentalities in Nova Scotia, Canada.

I begin the chapter by introducing ocean science. I then highlight a disconnect between science policy and industrial policy that occurred in Nova Scotia 5 years ago. There are often "overlaps and blurred boundaries" (Dodgson, 2000, p. 230) between public policies that promote science in universities and PROs—i.e., science policies[10], public policies that promote further development of key technologies—i.e., technology policies[10], and public policies that aim to promote the effectiveness of innovation systems—i.e., innovation policies[10] (Dodgson, 2000; Lundvall & Borrás, 2005). In Canada, these science, technology, and innovation (STI) policies are orchestrated by regional networks that involve federal, provincial, and local policy actors (Salazar & Holbrook, 2007). However, the smaller provinces—including Nova Scotia—are not active in science policy—it is left to the federal government (Sá, 2010; Salazar &

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[10] See also the definitions in the glossary.

Holbrook, 2007)[11]. Meanwhile, technology and innovation policies are defined under the umbrella of industrial policy (Edquist & Chaminade, 2006; Salazar & Holbrook, 2007). Although the provinces are active in industrial policy, it is a realm of economic policy and therefore a federal responsibility under the Canadian constitution (Salazar & Holbrook, 2007). Within this complex policy environment, it is essential that regional policy networks function effectively (Salazar & Holbrook, 2007). But several years ago, there was a clear disconnect in Nova Scotia between federal policies regarding ocean science and provincial/local policies regarding ocean technologies and ocean industries.

In 2012, ocean science was deprioritized alongside other environmental sciences under federal science policy (Bailey et al., 2016; Turner, 2013). At the same time, ocean technologies became the top priority under provincial and municipal industrial policy (Government of Nova Scotia, 2012; Greater Halifax Partnership, 2012). Ocean technologies had been identified as a federal industrial policy priority several years earlier (Atlantic Coastal Zone Information Steering Committee, 2006). These policy directives led to less ocean science activities in the region but greater attempts to build ocean technology industry. Similar divergences in STI policy have been observed during major government transitions in Ghana (Amankwah-Amoah, 2016) and in the present-day STI

[11] Under the Canadian constitution, provincial governments have full authority over education. This shapes a separation of responsibilities with respect to key elements of science policy; the provinces govern universities and fund their operating budgets while the federal government provides project-based funding for university research (Sá, 2010; Sá & Litwin, 2011; Salazar & Holbrook, 2007). The federal government also operates many of its own PROs across the country, but only certain provinces—i.e., Quebec and Alberta—have extensive science policy programs that include both provincially-funded university research programs and provincially-governed PROs (Sá, 2010; Salazar & Holbrook, 2007).

policies of France and Italy (Bianchini & Llerena, 2016). I argue that the disconnect in Nova Scotia was a policy gap—a gap in understandings about the relationships between science policy and industrial policy. This gap underscores the importance of studying this context. The importance of this gap will be further emphasized after I discuss the history of interactions between four ocean science PROs and several private scientific instrumentality companies in the province. At the end of the chapter I consider the implications of this history for the three propositions developed in Chapter 2, and I develop a fourth proposition that combines theory with what I have learned about the history of ocean science instrumentality innovation in this region.

Ocean Science

The province of Nova Scotia on Canada's Atlantic coast has long been recognized as a world-leader in ocean science and related technologies (Trenbirth, 1960; Watkins, 1980). Indeed, in 1980, *Canadian Geographic* magazine heralded the provincial capital region as "one of the three biggest marine science centres in the Western Hemisphere […] outnumbered in the Americas only by the Boston-Woods Hole area in Massachusetts and perhaps the Scripps Institution in California" (Watkins, 1980, p. 12). This reputation emerged during and shortly after World War II when the Government of Canada established substantial defense and civilian ocean science operations in the provincial capital of Halifax. The success of three federally-funded research organizations — the Naval Research Establishment (NRE), Dalhousie University's Oceanography Institute, and the Bedford Institute of Oceanography (BIO) — encouraged the provincial government's Nova Scotia Research Foundation (NSRF) to increasingly focus its efforts on ocean science and technology. Later in this chapter, I investigate the history of these four PROs. But first, it is helpful to understand the evolution and nature of their research.

In his autobiographical history of oceanography, ocean scientist and engineer William Bascom credits four factors with the rapid growth of ocean science after World War II: a “doubling” in submarine warfare, a “tripling” of the global fish catch, the shift to offshore oil production, and a new public interest in marine conservation & archaeology (Bascom, 1988, p. xiv). Dalhousie University Professor Emeritus Eric Mills uses a slightly longer list in his history of the field (Mills, 2011). He writes that due to demand from “fisheries, shipping, sewage disposal, ocean mineral exploitation, and submarine warfare, the field had expanded too rapidly for the supply of personnel from the pure sciences to keep pace” (Mills, 2011, p. 254). These two lists provide examples of the many ways in which humans relate to the ocean. The ocean is enacted in so many ways, that it is difficult to establish a single definition of ocean science.

Benson and Rehbock (1993) claim that “oceanography is a hybrid, a mixed science [that] cannot be said to be a single scientific discipline” (p. ix). Bascom (1988) claims that “oceanography is not so much a science as a collection of scientists” (p. xiii). Within the broad realm of oceanography, there are groups of oceanographers who are focused more or less on physical, biological, or chemical processes. For example, Mills (1994) compares the mix of scientists during the earliest days of oceanography at Dalhousie University and the University of British Columbia (UBC). At UBC, oceanography was primarily a physical science; it was grounded in physics. By contrast, oceanography was primarily a biological science at Dalhousie; and early oceanography leaders at Dalhousie were focused on marine biology and microbiology. Dalhousie’s present-day oceanography department studies a broad range of biological, chemical, and physical processes in the ocean. But oceanography is also not the only department at Dalhousie that houses ocean scientists. For example, among the many members of the biology department are several scholars of marine biology. Interestingly, many "marine biologists" appear not to accept the label "oceanographer," which they reserve primarily for "physical oceanographers" (not "biological oceanographers").[12] Because these labels have the potential to cause some difficulty, I use a broad and inclusive definition of ocean science. I follow the lead of the Council of Canadian Academies (Expert Panel on Canadian Ocean Science, 2013) in using the term "ocean science" to capture the full range of chemical, biological and physical scientific investigations of the ocean and its contents.

Ocean science is not framed by traditional scientific disciplines. Instead, it is framed by its research context—the ocean—and the problems found therein. In other words, ocean science is oriented toward "missions," such as tracking the migration of particular species (e.g., S. J. Cooke et al., 2011; O'Dor & Stokesbury, 2009), considering the potential impacts of industrial activity on marine life (e.g., Stokesbury et al., 2016), identifying and protecting sensitive marine areas and coastal zones (e.g., Greenlaw, Roff, Redden, & Allard, 2011), or assembling a "Census of Marine Life" (Vermeulen, 2013). Michael Gibbons and his colleagues have labelled this kind of science "Mode 2" (1994, 2000; Helga Nowotny et al., 2003; Helga Nowotny et al., 2013); and John Ziman has

[12] This point is thanks to two anonymous participants in a separate study (MacNeil, 2014b).

called it “post-academic science” (1996). Both labels refer to a shift in norms away from isolated individual specializations and toward interdisciplinary team-based scientific investigations with clear societal application, such as environmental protection. Interestingly, Olle Edqvist (2003) has argued that this is not a new set of scientific norms but rather a return to the traditional mode of scientific practice.

The ocean is critical to our climate and our economies, and so ocean science has important societal applications (Florizone & Cullen, 2014). But only 7 years ago, scientists knew “more about the backside of the moon than about our deep oceans” (Alexander, Miloslavich, & Yarincik, 2011, p. 545). Seventy percent of the Earth lies beneath the ocean, and yet at the turn of the 21st century, “oceanographers estimated that only 5 percent of the ocean had been systematically explored for life” (Ausubel, Trew Crist, & Waggoner, 2010, p. 6). Ocean science can be motivated by specific societal applications (Florizone & Cullen, 2014) and by curiosity regarding the unexplored parts of our planet (Ausubel, Trew Crist, & Waggoner, 2010).

The Policy Environment

Ocean science policy. Unfortunately, ocean science can also be undermined by the application of neoliberal ideas to public policy. Over the past decade in Canada, neoliberal ideology has fueled a “War on Science” (Turner, 2013). Chris Turner (2013) argues that in the early 2010s the Government of Canada exhibited “mounting disdain for the work of its scientists” (p. 17) and enacted “vicious cuts” (p. 26) to public research organizations, particularly those within the Department of Fisheries and Oceans. He suggests that this “war” was punctuated by federal budget legislation, Bill C-38, “tabled” five years ago:

> No scientist working on a federally funded project in the spring of 2012 could have been wholly complacent about their job security, especially if their field was in the environmental sciences. Bill C-38 had unleashed a broad frontal assault on the Canadian environmental science community. Tabled in the House of Commons six weeks earlier, the bill had triggered wave after wave of closures and “affected letters” (notices of potential or impending layoff) at research institutes, monitoring stations, and government labs across the country. (Turner, 2013, p. 8)

Science journalist Hannah Hoag describes these cuts as a policy shift away from basic science and toward applied partnership with industry (Hoag, 2011, 2012, 2013). This is further to a global trend in science policy (Archibugi & Filippetti, 2017; Sá & Litwin, 2011). Bailey et al. (2016) have also suggested that leadership in the Canadian government was attempting to “devolve” ocean science activities to universities and the private sector. They explain that these cuts have served to “eviscerate Canada’s federal aquatic science programs—staff reductions, closures of laboratories, closures of marine science libraries, and cessation of key research programs” (Bailey et al., 2016, p. 1). This, too, is further to a global trend in science policy—a shift of resources toward universities research labs and away from other types of PROs (Archibugi & Filippetti, 2017; Salazar & Holbrook, 2007).

Turner argues that this shift in policy was grounded in the belief that “the purpose of research—of science generally—is to create economic opportunities for industry, and the purpose of government is to assist in that process in whatever way that it can” (Turner, 2013, p. 112). He describes movement away from “the open spirit of scientific inquiry” (p. 132) toward the view that “government’s job is to deliver innovations like theatre tickets to the front desk of a posh hotel” (p. 112). In other words, those in power came to believe that PROs exist to serve the market. This belief has been linked to new public management (NPM)—a particular set of neoliberal strategies that were popular across OECD countries for decades.

NPM is a label applied to a "set of broadly similar administrative doctrines which dominated the administrative reform agenda in many of the OECD group of countries from the late 1970s" (Hood, 1991, pp. 3-4). The NPM agenda has been studied and critiqued as a set of organizational innovations in the public sector (Hansen, 2011; Lorenz, 2012; Schubert, 2009). NPM has been directly linked with neoliberalism because NPM reforms were intended to make public organizations more business-like (Atkinson-Grosjean, 2006; Lorenz, 2012). While the effectiveness of NPM is debateable (Hood, 1991; Lorenz, 2012; Schubert, 2009), it is accepted that NPM reforms had a substantial effect on the management and organization of public science in Canada beginning in the 1980s (Atkinson-Grosjean, 2006) and 1990s (Smith, 2004). In these previous waves of reform, public science was reorganized and increasingly aligned to private interests (Atkinson-Grosjean, 2002, 2006). The recent wave of reforms have resulted in substantive cuts to PROs across the country, and particularly to those PROs that were engaged in ocean science (Turner, 2013). Daniele Archibugi and Andrea Filippetti (2017) recently discussed these "neoliberal forces" (p. 98) and argued that the decline in public science globally will have "long term adverse consequences" (p. 12) for development.

Ocean industry policy. The ocean science budget cuts are especially disconcerting in the province of Nova Scotia. As I have noted, Nova Scotia developed a global reputation as a leader in ocean science after decades of work by several key PROs. And, ironically, at the same time as public policy was leading to reduced activities in ocean science, public funds were increasingly invested in ocean technology development. In

2012, the Government of Nova Scotia identified “ocean technologies” as a priority sector for economic development (Government of Nova Scotia, 2012). During the period of cuts to ocean science, ocean technology also became a priority development sector for the capital city’s economic development agency (Greater Halifax Partnership, 2012) and it had already been a priority for the federal government’s Atlantic Canada Opportunities Agency (ACOA) (Atlantic Coastal Zone Information Steering Committee, 2006). Science policy and industrial policy were moving in opposite directions. This is ironic because the province’s ocean technology industry evolved around the PROs.

Nova Scotia’s present-day ocean technology companies are said to have high levels of R&D intensity and to maintain close connections with public research organizations (Government of Nova Scotia, 2012). This idea is in stark contrast to the “maritime clusters” that have been studied in numerous jurisdictions around the world, including Norway (Benito, Berger, de la Forest, & Shum, 2003), Malaysia (Othman, Bruce, & Hamid, 2011), Japan (Shinohara, 2010), Wales (Cooke, Porter, Cruz, & Pinto, 2011), the Southwest region of England (Chang, 2011), the Huelva and Basque regions of Spain (P. Cooke et al., 2011), the Border-Midland-Western region of Ireland (P. Cooke et al., 2011), and the Norte and Algarve regions of Portugal (P. Cooke et al., 2011). These studies emphasize that “maritime clusters” are generally industrial districts (see Marshall, 1890) with low R&D intensity and are built around shipbuilding or offshore oil & gas facilities. A rare few of these clusters are defined around other extractive industries, such as the fishery. These studies use a neo-Marshallian industrial clusters theoretical framing. The innovation systems approach has been used to study three ocean technology innovation systems in Canada. Regional ocean technology innovation systems have been described as "low-innovation" in Quebec (Doloreux, 2008; Doloreux & Melançon, 2008), lacking in private-sector activity in British Columbia (Doloreux & Shearmur, 2009), and overly reliant on the offshore energy industry in Newfoundland (Doloreux & Shearmur, 2009). Ocean science instrumentalities are not a consideration in these maritime clusters and ocean technology innovation systems studied in other parts of the world. As will become clear in this chapter, Nova Scotia is different from these other regions due to the presence of interactive learning around scientific instrumentalities. Without this specialization, it might be possible to justify a disconnection between the relevant science policies and industrial policies in Nova Scotia. However, my third theoretical proposition—about the symbiotic nature of scientific instrumentality innovation—suggests that this disconnect may be a problem. There may be a gap in policy-makers' understanding about the relationships between ocean science and ocean technologies.

This policy gap is widened by the many possible ways of defining ocean technology. Defining Nova Scotia's ocean technology sector has been a long-standing challenge for regional policy makers. A 1979 report by the Nova Scotia Research Foundation (NSRF) expressed frustration that

> ocean industry is not a well-defined industrial sector. There is no standard industrial classification (SIC) covering the ocean industry nor are there official statistics for the industry. (NSRFC, 1979, p. 2)

Despite these problems, many different definitions of "ocean technology" are currently in use by public organizations and industry associations in North America. These organizations attempt, in their own ways, to define one coherent industry out of myriad different ocean technologies. In a 2012 policy statement, the Government of Nova Scotia defined its ocean technology sector as those private companies that operate in six technological fields: “acoustics, sensors, and instrumentation; marine geomatics; marine biotechnology; marine unmanned surface and underwater vehicles; marine data, information, and communications systems; and naval architecture” (Government of Nova Scotia, 2012, p. 5). Different definitions are used by the Government of Canada’s Atlantic Canada Opportunities Agency (ACOA) (Atlantic Coastal Zone Information Steering Committee, 2006), the Ocean Technology Council of Nova Scotia (OTCNS) (Ocean Technology Council of Nova Scotia, 2014), the ocean technology industry association for the neighbouring Province of Newfoundland and Labrador (OceansAdvance, 2014), and the United States of America’s National Oceanic and Atmospheric Administration (NOAA) (ERISS Corporation & The Maritime Alliance, 2014). All these definitions are exceedingly broad.

This dissertation maintains a focus on one field of technological application: ocean science instrumentalities. I have argued that this field of technology is potentially revelatory with respect to public innovation in goods and services. In this section I have added another reason for studying this context: it is also revelatory with respect to the gap between science policy and industrial policy in this region. A brief review of the history of ocean science instrumentality innovation in Nova Scotia will further highlight the important connections between ocean science PROs and scientific instrumentality companies in the region.

Regional History

Before investigating Nova Scotia’s present-day ocean science instrumentalities innovation system, I wanted to understand the historical context. Research on regional innovation systems typically includes some discussion about the history of a context before engaging with primary data. But readers are typically asked to take the authors' expert knowledge of the historical context for granted. I disagree with this approach. Instead, I follow the historical turn in organization studies (Booth & Rowlinson, 2006; Durepos & Mills, 2011) and specify my historiographic methods. My analysis of this data did not necessarily follow a linear or chronological approach, but my approach was systematic in terms of the identification of key discoveries or technological breakthroughs and in the identification of the organizations involved (see Appendix A). My theoretical framework was the focusing device, and my goal was to identify traces of interactive learning between organizations involved in scientific instrumentality innovation. My findings relate to the activities of four PROs: Naval Research Establishment, Nova Scotia Research Foundation, Dalhousie University, and Bedford Institute of Oceanography.

Naval Research Establishment. The oldest PRO identified in the historic records was the Naval Research Establishment (NRE). The NRE was established during World War II when two Dalhousie University physics professors were seconded to the Navy by way of the National Research Council (DREA, c. 1985; Longard, 1993). Their work during WWII and the Cold War was not in the field of scientific instrumentalities. NRE was engaged in what is commonly referred to as security or defense R&D (see Mowery, 2009, 2012).[13] However, in the limited records available[14] there is one innovation that had clear applications as a scientific instrumentality: variable depth sonar (VDS). A VDS "towed-sonar" system was developed and tested by Defense Research Establishment Atlantic (DREA), the renamed NRE. Tests were also conducted in partnership with the Bedford Institute of Oceanography in the early 1970s (BIO, 1962-1992). Then, DREA began working with Cossor Canada Ltd., later known as Hermes Electronics and now Ultra Electronics Maritime Systems, to build commercial units. These units were primarily for defense customers, but were also sold to public research organizations. Gaede and Merklinger (2003) explain that DREA's long-term relationship with Hermes was critical to the company's development: "DREA work kept engineers challenged during otherwise slow business periods, and the leading-edge nature of the DREA work helped to develop capabilities and components that found their way into Hermes products" (p. 143).

[13] Resulting in (1) a technique for degaussing the hulls of ships—now used worldwide, (2) improvements to ASDIC/SONAR detection of submarines, (3) the development of advanced sonobuoy systems for detection of submarines, (4) licensable patents for sea water battery and electroplating technologies, and (5) several functional prototypes of a hydrofoil craft (Longard, 1993).

[14] The nature of naval defense research means that official records are still not easily accessible. But after the cold war ended, an "unofficial" history that had been written in the early 1970s was published by Defence Research Establishment Atlantic (Longard 1993). A second "informal" history was published in 2003 covering the period from 1968 to 1995 (Gaede & Merklinger, 2003). The Nova Scotia Archives also house a short publicity document, circa 1985, which describes DREA inventions and industry partnerships (DREA, c. 1985). This booklet is undated, but includes a loose insert organizational chart dated 10 Sept 1985. These three documents provide a limited glimpse at decades of somewhat secretive ocean research. The WWII beginnings of naval research in Halifax are told in a very similar way by Mills (2011).

Under its various names, NRE, DREA, and now Defence R&D Canada (DRDC) Atlantic, also played important roles in supporting research at NSRF, BIO, and Dalhousie. The most important of these was the naval research vessels that were used for joint research missions (BIO, 1962-1992; NSRF, 1946-1995). Historians of science also credit this organization (Mills, 2011) and other naval research organizations—particularly in the USA (Benson & Rehbock, 1993; Hamblin, 2005; Weir, 2001)—with establishing physical oceanography as a scientific discipline.

Nova Scotia Research Foundation. The three other PROs examined in this chapter also had their origins in the period following World War II. The Nova Scotia Research Foundation (NSRF),[15] for example, was part of the provincial government's post-war economic development programme (Campbell, 1950; Tory, 1944; Woods, 1946). The NSRF (1946-1995) was originally established to conduct applied research and improve productivity in primary industries. But in the 1960s, Dr. J.E. Blanchard joined NSRF from the Oceanography Institute at Dalhousie University. After his promotion to President of NSRF in 1968, focus began to shift toward the manufacturing of innovative ocean technologies (NSRFC, 1979). This work was organized into a Centre for Ocean Technology at NSRF, led by C.R. Tyner who had previously been employed as an engineer at Hermes Electronics, E.M.I. Cossor Canada, and the Canadian Marconi Corporation.

[15]The NSRF was replaced by the Nova Scotia Innovation Corporation (Innovacorp) in 1995. Innovacorp does not use or produce ocean science instrumentalities.

However, like the NRE, the NSRF did not have a mandate to produce ocean science: its role was to stimulate the economy through R&D. Ocean technologies were developed for a wide range of non-scientific applications in the fishery and offshore energy sectors.[16] But NSRF's annual reports (1946-1995) also discuss three inventions that were used as scientific instruments. The first of these was a device to measure ocean waves called the "Wavestaff." In 1975, the intellectual property related to this device was licensed to local company Orion Electronics, a company that was later acquired by British defense company Cobham PLC. Second, an entire line of slip ring and rotary joint products was developed. These are important components for connecting ocean instrumentation to data and control cables. The patented technologies were licensed to Focal Technologies Inc. (which is now part of MOOG Components Group) in 1987/1988. Several NSRF employees also moved to Focal, where their first customer was the BIO. The third scientific instrumentality, a deep-towed system to profile the ocean floor, was originally developed for the offshore energy sector but also proved useful in scientific investigations. NSRF rented the original system, nicknamed "V-Fin," to the offshore industry and to local PROs such as BIO and Dalhousie University. The prototype, spare parts, and intellectual property were transferred to an unnamed British company in 1991 (NSRF, 1946-1995). Note that the development of NSRF's three scientific instrumentality

[16] NSRF's many inventions included: a series of electrical slip rings and rotary unions (originally licensed to an unnamed local diving equipment manufacturer, which would later go bankrupt), an oil spill tracker, an HS2-in-water meter (licensed to K.W. Colwell Ent. Ltd.), a corrosive detector fuse, a dried-fish chip snack food, an x-ray fish bone detector, fibre optic rotary joints (licensed to Focal Technologies in 1983/1984), a survival suit test manikin, an electronic fish jigger (licensed to ABCO Industries Ltd.), and magnetic coupling drives (spun-off as the company Nova Magnetics).

innovations did not involve symbiotic relations: the three devices above were transferred to private companies via one-way flows of IP and equipment. However, NSRF did seem to maintain close symbiotic relations with the other three PROs in this study: they shared information, engaged in joint R&D, and shared capital equipment.

Dalhousie University. A decade of negotiations between 1949 and 1959 resulted in funding to establish the Dalhousie University Oceanography Institute (Hayes, 1959). The announcement of this new institute appeared in the journal Nature and proudly proclaimed,

> All branches of marine science will come under investigation, and opportunities for work at sea will be provided by the Royal Canadian Navy, the Fisheries Research Board of Canada, and other agencies. (Hayes, 1959, p. 1161)

Dr. Ron Hayes pulled together faculty from the departments of biology, chemistry, physics, and geology, including geologist Dr. J.E. Blanchard, who later became President of the NSRF. A decade later, the University began building a new life sciences building which would become home to the Oceanography Department and a large salt water research tank called the “Aquatron” (Waite, 1994). In its early years, the Oceanography Department interacted with industry primarily through the graduates of its programs. However, no specific student employment announcements can be found in the archival sources or published histories. Dalhousie had more symbiotic relations with NRE, NSRF, and BIO, which involved joint research projects, information exchanges, and the exchange or sharing of equipment and technical services.

The university began engaging more closely with industry from the 1980s onward (see Department of Oceanography, 2011). Various instrumentality companies were established by scientists in the oceanography department, including Pro-Oceanus Systems Inc., Nortek Scientific, and Satlantic LP, which was later acquired by American instrumentalities firm SeaBird Scientific. Meanwhile, marine biology Professor Ron O'Dor developed "radio-acoustic positioning and telemetry" technology (O'Dor et al., 1998) to aid in his tracking of aquatic animals. This resulted in the establishment of Vemco, an operating division of AMIRIX Systems Inc., which itself was a joint creation of Dalhousie, the NSRF, and the Technical University of Nova Scotia, which was later integrated into four units of Dalhousie University.

Bedford Institute of Oceanography. The fourth PRO that I identified in historical documents is the Bedford Institute of Oceanography (BIO). BIO was established in 1959 to bring together various federal PROs engaged in oceans-related research for the purposes of "science, defence, commerce, and development of the country's resources" ("Canadian Institute of Oceanography," 1959). The establishment of BIO coincided with federal funding for Dalhousie University's Oceanography Institute. While the elected officials encouraged cooperation between the two, the Deputy Minister publicly urged that a university scientist should remain "free to tackle *any* problem" [emphasis in original] (van Steenburgh, 1962, p. 10) based on its scientific merits. Meanwhile, he explained that BIO's research programs would be aligned to politically-mandated agendas. Over the years, employees from over several different public organizations would be housed under the umbrella of BIO while maintaining their departmental/agency designations. At its height, nearly 700 employees were sharing the BIO facilities and research vessels, one of which was on loan from the Canadian Navy. Researchers from

NRE/DREA/DRDC, the NSRF, and Dalhousie University were also welcome aboard the research vessels.

Aside from the research vessels, most instruments and equipment required by BIO scientists had not been invented in the 1950s. From the 1960s through the 1980s, a group of engineers and technicians operated within BIO to develop a variety of technologies that were required by BIO scientists. These included “an underwater rock-core drill, instrument mooring methods and materials, baseline acoustic positioning systems, oceanographic sensors, and seismic profilers” (BIO, 2002, p. 16). These engineers and technicians developed technologies for use within BIO, but they also had an interest in commercialization. Many projects developed in partnership with the private sector and then marketed internationally (BIO, 2002). One early invention, the Guideline Salinometer, was soon “found in every oceanographic laboratory in the world” (BIO, 2002, p. 25). BATFISH, a towed variable-depth sensor package, was another early-years partnership with Guideline Instruments Ltd. of Smith’s Falls, Ontario (BIO, 1969-1970; Watkins, 1980).

During the 1970s, major breakthroughs were developed with, or transferred to, local industry in Nova Scotia. These included a meteorological buoy with Hermes Electronics and an ocean bottom seismometer with the Canadian Marconi Company (BIO, 2002). John Brooke led instrument development at BIO and became BIO’s “Industrial Liaison Officer.” He also sat on an advisory board at NSRF. Upon his retirement in the early 1980s, he founded the company Brooke Ocean Technologies which became a symbiotic partner for the BIO. Brooke Ocean Technologies was later acquired by the Norwegian ocean technology company Odim ASA, which was then acquired by Rolls Royce Naval.

Rolls Royce Naval reduced its ODIM Brooke Ocean operation to a small sales support team in 2015 (Brooks, 2015). However, during their time together, BIO and Brooke Ocean developed two key ocean science instruments: a “Moving Vessel Profiler System” that improved on BATFISH, and a wave-powered profiler called SeaHorse.[17] Over the subsequent years, other local industry partners engaged in technology development partnerships with BIO including MetOcean Data Systems and Open Seas Instrumentation.

But BIO’s purpose was to engage private sector resources in developing oceanographic tools, not necessarily to establish a local industry. Throughout the 1980s, partners and contractors outside of Nova Scotia were also involved in interactive learning related to new technologies, including a deep-towed seismic system that was developed with Huntec Ltd. of Scarborough, Ontario,[18] advancements in marine GIS software with Universal Systems Ltd. (also known as CARIS) of Fredericton, NB, and the DOLPHIN and ARCS underwater autonomous vehicles developed with International Submarine Engineering Ltd. of Port Moody, BC. BIO’s interactive learning relationships extended well beyond the local region.

Implications of this Chapter

The historical records discussed above highlighted many instances of interactive learning between four PROs and various private companies. There were also many

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[17] This Government of Canada patent (US Patent No. 5644077) was licensed to Brooke Ocean. See http://www.bio.gc.ca/science/newtech-technouvelles/seahorse/index-eng.php

[18] Although it looks like some of the Huntec knowledge returned “home” to Nova Scotia. The company collapsed sometime around 1985, prompting former employee Dr. Peter Simkin to found IKB Technologies, which moved to Nova Scotia in 1998 (see http://www.seistec.ca/images/Corporate%20Profile2007.pdf).

instances of interactive learning between the PROs themselves. For each PRO, I developed a list of the external partners involved in key discoveries or technological breakthroughs. The relevant channels of interaction between each PRO and its partner organizations were identified based on the way the interaction/relationship was described in the archival records. The interactive learning relationships were coded into the channels of interaction framework found in Table 2 above. The results of this coding are summarized in Table 3. The relational data in Table 3 was then assembled into Figure 4, which provides a network illustration of several organizations and relationships that contributed to the evolution of this innovation system. This historical evidence provides preliminary support for the three theoretical propositions developed in Chapter 2.

Support for propositions 1, 2, and 3. Further to proposition 1, the historical evidence suggests that PROs may have been the most important actors in a scientific instrumentality innovation system. The importance of these PROs is evident in the central positions the hold in Figure 4. Note, however, that the historical records reviewed in this chapter were primarily produced by the PROs; their importance in the innovation system may simply reflect the authorship of the course material. This evidence therefore provides only qualified support for proposition 1.

The support for proposition 2 is stronger. I had proposed that the interactive learning between PROs and scientific instrumentality companies involves multiple channels and is bidirectional. In other words, the relationships are expected to be symbiotic. The final right-hand column of Table 3 lists the private companies that had multiple types of interactions with each PRO and where the interactions were bidirectional. In total, I observed thirteen relationships between PROs and companies that were symbiotic and 5 that were not. This lends support to proposition 2.

Table 3

Channels of Interactive Learning used by Four Public Research Organizations

	R&D Projects and Consultancy Channel	Intellectual Property Rights Channel	Human Resources Channel[1]	Information and Training Channel[2]	Capital Equipment and Technical Services Channel	Symbiotic PRO-I Relations
Naval Research Establishment[3] (NRE, later known as DREA, DRDC)	– Cossor – NSRF – BIO – Dal	– Cossor	– Dal – NSRF	– NSRF – BIO – Dal	– Cossor – NSRF – BIO – Dal	– Cossor
Nova Scotia Research Foundation (NSRF)	– NRE – BIO – Dal	– Orion Electronics – Unnamed British Company – Focal Technologies	– Dal – NRE – BIO – Hermes[4] – Focal Technologies	– NRE – BIO – Dal	– NRE – BIO	
Bedford Institute of Oceanography (BIO)	– NSRF – Guideline – Huntec – Brooke Ocean – MetOcean – Open Seas – Int'l Submarine – Universal Systems	– Guideline – Huntec – Hermes – Marconi – Brooke Ocean	– Dal – NSRF – Brooke Ocean	– NRE – NSRF – Dal	– NRE – NSRF – Dal – Guideline – Hermes – Huntec – Brooke Ocean – MetOcean – Open Seas – Int'l Submarine – Universal Systems – Focal Technologies	– Guideline – Hermes – Huntec – Brooke Ocean – MetOcean – Open Seas – Int'l Submarine – Universal Systems

	R&D Projects and Consultancy Channel	Intellectual Property Rights Channel	Human Resources Channel[1]	Information and Training Channel[2]	Capital Equipment and Technical Services Channel	Symbiotic PRO-I Relations
Dalhousie University (Dal)	– NRE – NSRF – BIO	– Vemco[5] – Satlantic[5] – ProOceanus[5] – Nortek[5]	– NRE – NSRF – BIO – Vemco – Satlantic – ProOceanus – Nortek	– NRE – NSRF – BIO – Vemco[6]	– NRE – NSRF – BIO – Vemco – Satlantic – ProOceanus – Nortek	– Vemco – Satlantic – ProOceanus – Nortek
Total PRO-I Relations	8	13	7	1	14	13

Notes. (1) Dalhousie University is the only degree-granting PRO in the region and therefore has HR channel relationships (via student mobility) with other organizations. Evidence of student mobility to the private firms was not included in this study. Note that the HR channel also includes non-student employee mobility and shared human resources among organizations; (2) The secondary sources that were examined provided little evidence of informal information flows. However, formal information exchanges were evident among the 4 PROs and between Dal and Vemco (in the form of a co-authored publication); (3) Secondary sources for NRE were limited; (4) C.R. Tyner joined NSRF after work at Hermes Electronics. He had previously been employed at Cossor and Marconi. There may be other movement of human resources in this innovation system that is not captured in the published sources; (5) Scientific instruments invented by Dalhousie researchers were further developed by Vemco, Satlantic, ProOceanus and Nortek. However, at Dalhousie, IP owned by the researchers themselves and so the interaction is technically between companies and individual researchers (not the university as a corporate entity); (6) An academic journal article was coauthored between Dalhousie researchers and Vemco employees (O'Dor et al. 1998).

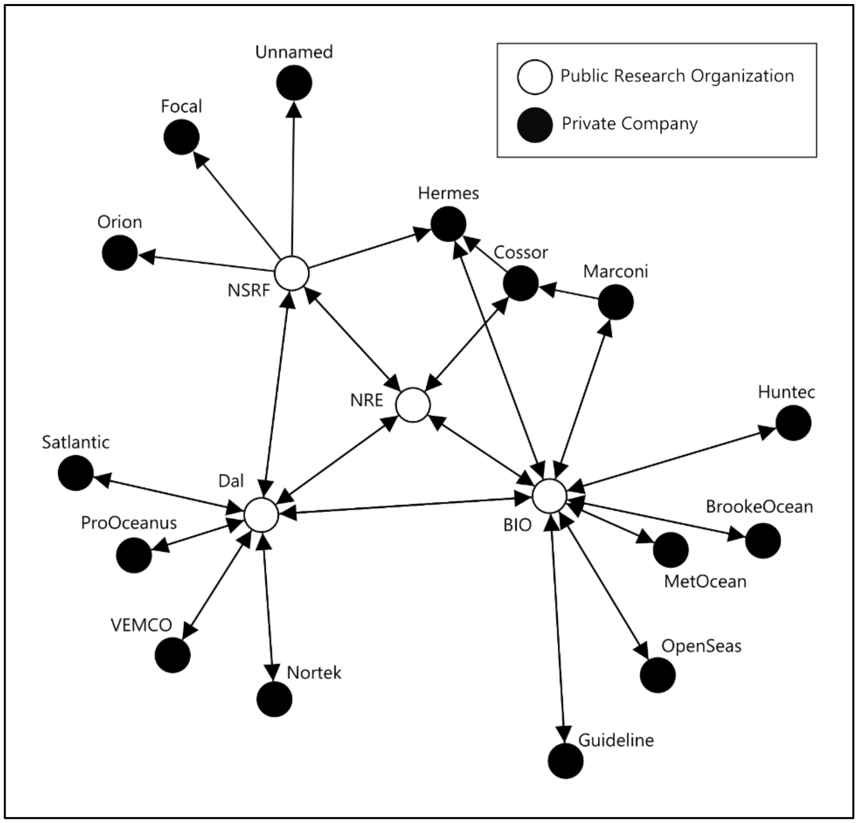

Figure 4. Instances of interactive learning in ocean science instrumentalities identified from historical records for Nova Scotia, Canada. Author's own work, rendered from secondary sources (see data in Table 3) using Gephi (Gephi Consortium, 2012) and the ForceAtlas 2 layout algorithm (Jacomy, Venturini, Heymann, & Bastian, 2014).

The historical evidence also lends support to proposition 3: the most important interactive learning channel does appear to be the provision and acquisition of capital equipment and technical services. I identified fourteen instances of PRO-industry interaction involving the provision or acquisition of capital equipment and technical services (see the bottom row of Table 3). This was the most frequently observed channel of interactive learning in the archival records. I also identified thirteen instances of formal intellectual property flows, eight instances of R&D projects and consultancy, seven instances of human resource movement or sharing, and one instance of formal information and training interaction. It is likely that informal interactions—especially those related to information sharing and training—may be under-reported in formal archival and historical records. Formal interactions, such as capital equipment and technical services or transfers of intellectual property, may therefore be proportionately overrepresented in the overall mix of interactive learning channels.

PROs as anchor tenants. Overall, the archival evidence suggests that PROs may have been the "locus of innovation" (von Hippel, 1976) for an ocean science instrumentalities innovation system in Nova Scotia. The PROs appear to be the central actors; the glue that held the system together. The four PROs were closely—and perhaps symbiotically—interacting with private companies and with each other as they each engaged in ocean science for different purposes. This overall characterization suggests that the PROs may have served as anchor tenants (Agrawal & Cockburn, 2003; Niosi & Zhegu, 2005; Niosi & Zhegu, 2010) in this innovation system. Anchor tenants are typically described as large private companies that are embedded in a regional innovation system and serve two functions: providing substantial knowledge spillovers and attracting other firms to the region (Agrawal & Cockburn, 2003; Feldman, 2003; Niosi & Zhegu, 2005; Niosi & Zhegu, 2010). However, Feldman (2003) and Niosi and Zhegu (2010) suggest that universities can also be anchor tenants. The notion that PROs might be anchor tenants in this system arises from my discussion of context; the concept of anchor tenants is not considered in prior research about scientific instrumentality innovation.

PROs have recently been identified as key actors in a static sense—in terms of their dominant or important position various systems: European nanotech (Bergé, Scherngell, & Wanzenböck, 2017), a Spanish science and technology park (Latorre, Hermoso, & Rubio, 2017), Chinese pharmaceuticals (Perri, Scalera, & Mudambi, 2017), global alternative energy patenting (Popp, 2017), German biotech (Roesler & Broekel, 2017), and the Chinese 3D printing industry (Xu, Wu, Minshall, & Zhou, 2017)[19]. This theoretical conceptualization of anchor tenants—based on their static position relative to other actors—is similar to von Hippel's (1976) "locus of innovation" concept and is captured in Proposition 1. However, the evidence discussed in this chapter suggests that this innovation system may be structurally dependent on PROs. This is a dynamic theoretical conceptualization of the anchor tenant role: the loss or reduction of a key PRO may have a greater negative impact across the whole innovation system than the loss of a private company. This possibility is highly relevant given my earlier discussion of drastic cuts to the region's ocean science capacity and substantive investment in the region's ocean technology industry. My theoretical and contextual discussions have both suggested that a scientific instrumentality innovation system may structurally dependent upon PROs, thus the cuts to ocean science may have important implications for ocean science instrumentality innovation.

There has not been enough research into the ways that innovation systems might be structurally dependant upon certain types of actors. Based on qualitative evidence,

[19] Of the recent articles cited here, only one uses the term "anchor" (i.e., Xu, Wu, Minshall, & Zhou, 2017).

Ferrary and Granovetter (2009) have suggested that Silicon Valley's innovation system is highly susceptible to the loss of venture capital firms. Powell, Packalen, and Whittington (2012) have shown, also qualitatively, that at one point in time the removal of PROs would have collapsed Boston's biotech innovation system. A key implication of the present chapter is to provide an opportunity for further research into the structural dependence of innovation systems. Given the research on scientific instrumentalities, and based on the historical evidence discussed in this chapter, I propose that

> **Proposition 4: A scientific instrumentalities innovation system is more susceptible to the loss of public research organizations than to the loss of other types of organizations.**

In other words, a combination of theory and context tells me that PROs should anchor this innovation system—the downsizing or removal of a PRO likely has greater system-wide impact than the downsizing or removal of a private company.

Companies as quartermasters. If PROs are indeed the anchor tenants in a scientific instrumentality innovation system, where does this leave private companies? In this chapter, I identified some instances where instrumentality innovations were produced within the PROs and then commercialized by industry, such as NSRF's wavestaff. This is consistent with the observations of von Hippel and his colleagues (Riggs and von Hippel, 1994; Spital, 1979; von Hippel, 1976; von Hippel, 1988). I also identify instances where PROs and instrumentality companies worked in close symbiotic relations, as in BIO and Brooke Ocean or Dalhousie and Vemco. PRO-industry relations were only simple and linear in the case of the NSRF; that is, several technologies were transferred to industry through the IPR channel. NRE, BIO and Dalhousie all established multiple types of bidirectional relations with scientific instrumentality companies, further to Proposition 2.

Also, NRE, BIO and Dalhousie have all engaged with industry to acquire capital equipment and/or technical services. This evidence supports Proposition 3: the equipment/services channel appears to have been central to the interactive learning between PROs and instrumentality companies. And so, if PROs are to be labelled as “anchors” in the innovation system, private companies can be labelled as “quartermasters,” like the individuals responsible for providing supplies to units in an army. Several private companies provided important instrumentalities for these four PROs. However, theory and historical evidence suggest that this relationship is more nuanced than simple provision of equipment and services. Indeed, the term “quartermaster” is used differently by navies: naval quartermasters help to navigate their ships. The theoretical framework developed in Chapter 2 and the historical records discussed in this chapter both suggest that the technical expertise provided by scientific instrument companies may help to set the course for science.

Limitations of the archival evidence. I say that these records only “suggest” a certain interpretation of the past because they are only partial traces of a previous time (Durepos & Mills, 2011; Durepos & Mills, 2012). Historiographic methods are generally taken for granted in innovation studies; papers and dissertations in this field often present historical context as succinct and indisputable fact. I have disagreed with this approach. Instead, I have been explicit about the materials and methods I used to write this context chapter. This helps readers understand why definitive conclusions should not be drawn from this chapter. The archival sources I use in this chapter are focused on the work of these PROs, not on the private companies, and most of the sources were published by the PROs themselves. Indeed, the centrality of the PROs in Figure 4 may be a function of the source material. This confirms how important it is to be explicit about the materials and methods used to produce contextual histories of innovation systems: it allows us to acknowledge limitations, as in any other research. For my research, the bias of historical records toward public organizations underscores the need for careful collection of primary data.

In the next chapter, I introduce analytical concepts that allow me to restate my four theoretical propositions as hypotheses. I can then test these hypotheses using data from the present-day interactive learning network in this regional-sectoral innovation system. The purpose of this chapter has been to provide a rich description of the empirical context that I use for the remainder of this dissertation. The context was shaped by the activities of four PROs over many decades. More recently, the context was shaped by critical shifts in public policy: the simultaneous prioritization of ocean technology industry and deprioritization of public ocean science. Following an analysis of the present-day innovation system, the final chapter of this dissertation returns to questions about the importance of PROs and the possible implications of a disconnect between science policy and industrial policy.

Chapter 4: Analytical Framework

The preceding chapters have considered both theory and context, enabling me to develop an analytical framework in this chapter. My analytical framework acts as a bridge between theory and method; it provides the foundation for data collection and analysis throughout the remainder of the dissertation. In what follows, I also describe the ways that I avoid a narrow market-orientation in my analytical work.

At its most basic level, the analytical framework developed here has become common place in innovation studies: I will use concepts and techniques from network science to analyze an innovation system. Like several other scholars, I treat a regional-sectoral innovation system as an interactive learning network (e.g., Cantner & Graf, 2006; Kaufmann & Tödtling, 2001; R. Martin & Moodysson, 2011a, 2011b) in keeping with a general trend in the use of network analysis for innovation studies (Kastelle & Steen, 2010; van der Valk & Gijsbers, 2010). However, I make important adjustments to ensure that my analysis is capable of surfacing public innovation. In the first section of this chapter, I take great care to define and differentiate between institutions—the "rules of the game"(North, 1990, p. 4)—and organizations—i.e., the "players" (North, 1990, p. 4). Some innovation scholars use the term "institution" in an atheoretical sense, thereby pushing PROs into the background of innovation systems (Edquist & Johnson, 1997). Instead, I conceptualize an innovation system as an institutional field in which many kinds of organizations engage in interactive learning. IN the second section of this chapter, concepts from network science allow me to approach interactive learning as more than a linear and dichotomous PRO-industry, or user-producer relationship. Instead, I frame interactive learning as a network phenomenon: the sum of many dyadic relations, allowing for key measurement concepts from network analysis to restate my earlier four theoretical propositions as hypotheses. In the final section, I conceptualize this innovation system as both an institutional field and a network, allowing me to address the problem of regional-sectoral boundary specification (Doloreux & Parto, 2005) by combining insights from innovation studies and network analysis. This third and final adjustment involves the careful definition of network/system boundaries. Together, these three adjustments provide an analytical framework that can investigate the importance of public organizations for scientific instrumentality innovation. The chapter concludes with a summary of this analytical framework.

Institutions and Organizations

In earlier chapters, I introduced core theoretical concepts related to innovation systems. I argued that this approach is appropriate for my work because it provides an alternative to the linear and firm-centric approaches that previously dominated the innovation studies literature (Fagerberg et al., 2013; Lundvall, 2013; B. Martin, 2013, 2016). An innovation systems approach allows me to take a system-level perspective: my analysis can be focused on interactive learning processes that are socially-embedded in a particular context (Lundvall, 1992). Using an innovation systems analytical approach first requires a closer look at the components of an innovation system. Carefully defining these components will provide the first important piece of my analytical framework.

Several innovation system scholars have pointed out that there are unfortunately two different uses of the term “institution” in the literature (Coriat & Weinstein, 2002; Edquist, 2001; Grønning, 2008). Some work uses the term in reference to a category of organizations (Edquist & Johnson, 1997; Grønning, 2008); it is frequently used as a euphemism for PROs (Coriat and Weinstein 2002). Other work speaks of institutions as the formal and informal rules that shape organizational interaction (Edquist & Johnson, 1997). For the purposes of clarity in this dissertation, I follow Charles Edquist and Bjorn Johnson (1997) in borrowing conceptual definitions from institution theory.

Nobel laureate Douglass North (1990) argued for a distinction between manifest institutions—i.e., organizations—and abstract institutions—i.e., rules. He said, "what must be clearly differentiated are the rules from the players" (North, 1990, p. 4) because any institutional theory must "begin with the individual" (North, 1990, p. 5) and focus on "groups of individuals bound by some common purpose to achieve objectives" (North, 1990, p. 5).[20] In short, his approach encourages the separation of organizations from the rules they follow. Edquist and Johnson (Edquist, 1997, 2004; Edquist & Johnson, 1997) argued that research on innovation systems should follow North's institutional theory approach. Based on North's work, Edquist and Johnson (1997) concluded that we should "deduct" legally constituted organizations from the organizing—the interactive learning—that occurs outside or between organizational entities. Similarly, Casper, Hollingsworth, and Whitley (2005) discuss a separation between institutions and "the interaction of individuals and groups within a particular institutional setting" (p. 197). If we fully deploy North's (1990) sports metaphor to an innovation system we can think of

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[20] Note that focusing on "organizations" rather than "individuals" introduces a potential "cross-level fallacy" (Rousseau, 1985) in the innovation systems approach. Meeus and Oerlemans (2005a) explain the potential fallacy this way: "although learning is based on individuals in the workforce of the firm, it is assumed firms can learn" (p. 159). Theoretical grounds for this assumption can be found in Nonaka and Takeuchi's (1995) "organizational knowledge creation process" which establishes links between individual-level and organizational-level learning behaviour.

organizations as the players, institutions as the rules, and interactive learning as the sport, or the play. I therefore define institutions as the rules of a particular playing field, and organizations as the teams of players (see also Glossary). Since the work of Edquist and Johnson (1997), there has been an "increasing consensus" within the innovation systems literature that institutions and organizations should be defined in this way (Grønning, 2008).

Positioning organizations as separable from institutions allows me to distinguish between types of organizations in an innovation system. The organizations in question often include public and private entities, but emphasis is placed on private firms (Edquist & Johnson, 1997). My analytical focus is on organizations broadly, and I allow the type of organization to be a variable rather than a predetermined filter. Further, I follow the OECD (2005) approach to identifying appropriate organizational units of analysis. This standard approach involves separating large heterogenous legal entities such as multinational corporations into their homogenous components (OECD, 2005). According to the third edition of the OECD's "Oslo Manual: Guidelines for Collecting and Interpreting Innovation Data" (2005), innovation data should be collected at the "kind-of-activity unit" (KAU) level, whenever possible. The KAU is

> …an enterprise or part of an enterprise which engages in one kind of economic activity without being restricted to the geographic area in which that activity is carried out. This means that the KAU may consist of one or more legal units, or a part of a legal unit (OECD, 2005, p. 66).

Note, again, that the standard unit of analysis in innovation research is the private sector enterprise. Nonetheless, the KAU concept is applicable to all types of organizational entities.

In this section I have shown that it is theoretically appropriate to treat innovation systems as institutional fields. Although the innovation studies literature is focused on private firms, innovation systems may also include other types of organizations, such as public research organizations, universities, and sometimes rule-creating public and not-for-profit organizations such as law-making bodies, and professional associations (Edquist & Johnson, 1997). Interaction between all of these types of organizations can be shaped by a wide range of formal institutions such as patent laws or technical standards, and informal institutions such as cultural practices or behavioural norms (Meeus & Oerlemans, 2005a). These formal and informal institutions vary across national, regional, and sectoral contexts (Meeus & Oerlemans, 2005b).

Interactive Learning Networks

I have described innovation systems as institutional fields in which organizations engage in interactive learning. In this section I will present my framework for analyzing an innovation system as an interorganizational network comprised of various organizations engaged in learning interactions (see also van der Valk & Gijsbers, 2010). For the purposes of network analysis, the organizations are represented by nodes and the interactions are represented by edges. If organizations A and B interacted with one another, an edge is present between those two nodes. Interactive learning can thereby be presented as a network graph or as an adjacency matrix similar to Table 4 (Borgatti, Everett, & Johnson, 2013; Hanneman & Riddle, 2005; Scott, 2000). The Boolean values in the adjacency matrix indicate the presence or absence of a learning interaction between two organizations. For example, a relationship is present in cells A-C and C-A. Also, a relationship is present in cell D-B, but not in cell B-D. This means that the relationship has a direction: D may have sold a piece of equipment to B, or a key employee may have left D for B. Each type of learning interaction is captured in a single matrix, but multiple matrices can be layered together in a single dataset. In this way, the multiple types of learning interactions that take place within an innovation system can be analyzed using a wide range of methods derived from graph theory.

Table 4

Sample Adjacency Matrix for Organizations A, B, C and D

	A	B	C	D
A		1	1	0
B	1		0	0
C	1	0		0
D	0	1	0	

Network analysis techniques hold tremendous potential for understanding the complexities of innovation systems (Kastelle & Steen, 2010). They are particularly well suited to examining patterns of interactive learning at a system level, rather than the organization/firm level. These techniques also promise to be powerful tools that policy makers can use for developing and evaluating innovation policy (van der Valk & Gijsbers, 2010). A network approach helps to overcome analytical limitations of linear and chain-link frameworks. Also, it has been argued that public innovation should be studied at the level of an organizational—or institutional—field (Hartley, 2005). However, network analysis methods have only begun to find their way into business (Bergenholtz & Waldstrøm, 2011) and innovation (van der Valk & Gijsbers, 2010) journals in the past decade.

Most of the recent network analyses of science-industry interaction (summarized in Appendix A) focus on patent and/or co-publication networks (e.g., Bergé, Scherngell, & Wanzenböck, 2017; Perri, Scalera, & Mudambi, 2017; Popp, 2017), despite the well-documented limitations of patent and publication data (see discussion in Ahuja, 2000; Katz & Martin, 1997; Moody, 2004). Furthermore, many of these recent studies employ only descriptive network analysis (e.g., Bergé, Scherngell, & Wanzenböck, 2017; Chang, 2017; Rothgang et al., 2017). There are however, emerging trends toward the collection of longitudinal network data (e.g., Choi, 2017; Roesler & Broekel, 2017; Töpfer, Cantner, & Graf, 2017) and statistical modelling of network data (e.g., Arza & Carattoli, 2017; Broekel & Mueller, 2017; Roesler & Broekel, 2017). Overall, network analysis remains relatively underutilized and underdeveloped in innovation studies (Bergenholtz & Waldstrøm, 2011; Glückler & Doreian, 2016; van der Valk & Gijsbers, 2010).

There are a few applications of network analysis in innovation studies that are worth highlighting. Sophisticated applications of network analysis have been used to expand our understanding of regional industry dynamics (Cantner & Graf, 2006; Giuliani, 2005, 2013; Giuliani & Bell, 2005), particularly university-industry interaction (Balconi, Breschi, & Lissoni, 2004; Breschi & Catalini, 2010; Giuliani et al., 2010; Kauffeld-Monz & Fritsch, 2013; van der Valk & Gijsbers, 2010). In innovation studies, network analysis has been used to evaluate the relative position of network actors (e.g., Balconi et al., 2004; Gay & Dousset, 2005; Gilsing et al., 2008; Salman & Saives, 2005; Takeda, Kajikawa, Sakata, & Matsushima, 2008), to identify the factors that influence a network's structural composition (e.g., Cantner & Graf, 2006; R. Martin, 2013; R. Martin & Moodysson, 2011a; Sorenson, Rivkin, & Fleming, 2006), and to understand the evolutionary dynamics of certain network structures (e.g., Ferrary & Granovetter, 2009; Giuliani, 2013; Giuliani & Bell, 2005). I address these three analytical approaches—network position, network composition, and network dynamics—in the following sections. Each approach corresponds with different theoretical propositions from earlier chapters.

Network position: Centrality. There are several ways to analyze an actor's position, or centrality, in a network. Centrality is "a family of concepts" that refer to the way that a node contributes to the structure of a network (Borgatti et al., 2013, p. 164). Recent network analyses of science-industry interaction have found that the relative centrality of PROs varies across systems: PROs are important biotechnology actors in both Germany (Roesler & Broekel, 2017) and Taiwan (Chen & Liu, 2012), they are the key nanotech actors in Europe (Bergé, Scherngell, & Wanzenböck, 2017) but not in South Korea (Choi, 2017), and universities are the central organizations in a Spanish science park (Latorre, Hermoso, & Rubio, 2017) but firms are the central organizations in a Chinese science park (Lyu, Wu, Hu, & Huang, 2017). For the Chinese 3D printing industry, PROs were found to be the "anchor players" in a scientific co-authorship network and in a co-patenting network, whereas firms were the "anchor players" in a network of business relations (Xu, Wu, Minshall, & Zhou, 2017).

For innovation networks, different measures of centrality have been used to assess the strategic importance of network actors. Two recent studies have developed different ways of calculating a centrality measure for innovation networks that uses the new theoretical concept of bridging centrality (see Bergé, Scherngell, & Wanzenböck, 2017; Broekel & Mueller, 2017). Bridging centrality might prove useful for future studies of innovation networks if consensus develops around a common mathematical approach. At present however, the two commonly used measures are degree centrality and betweenness centrality. Degree centrality is a simple measure of how well a node is connected to a network. It is the total number of relations between the focal node and other nodes in the network (Borgatti et al., 2013). Nodes with high degree centrality can therefore be described as highly engaged in the network. Betweenness centrality is different in that it measures the number of times that one node falls along the shortest paths between all other pairs of nodes. Nodes with high betweenness centrality therefore occupy key positions as brokers in a network: they can facilitate or disrupt flows between other nodes. These two centrality concepts can be complimentary. For example, Salman and Saives (2005) showed that both were positively related to innovation performance (i.e., patenting) for 40 biotech firms in Quebec. Also, Balconi et al. (2004) found that academic inventors had higher degree centrality and higher betweenness centrality than non-academic inventors in the Italian patent network. In other words, the academic inventors were more highly connected and more likely to hold brokerage positions. In this way, degree centrality and betweenness centrality sometimes appear to be interchangeable when they both correlate with an underlying third variable.

These measures are conceptually different and it is therefore important to select the centrality concept that is most relevant to the phenomenon under investigation. For example, Gilsing et al. (2008) wanted to understand how a firm's position in a biotech alliance network was related to its innovation performance. They chose to measure betweenness centrality and found that under the right network conditions, firms with high betweenness were in better positions to search for novel combinations of knowledge. This is consistent with the typical interpretation of betweenness centrality: that it represents a node's ability to control flows through a network—to act as a network broker (Borgatti et al., 2013). Meanwhile, degree centrality is typically interpreted as representing a node's importance or influence in a network (Borgatti et al., 2013). In one example from innovation studies, Takeda et al. (2008) found that a multi-sector regional innovation system in Japan was characterised by several firms with high degree centrality that each served as hubs for geographic agglomerations of related firms. In another example, Gay and Dousset (2005) examined a network of biotechnology industry alliances and found that the most highly connected firms—those with high degree centrality—were the most likely to attract additional alliances over time. This well-studied "rich-get-richer" property of real world networks is called "preferential attachment" (Barabási & Albert, 1999). However, Gay and Dousset (2005) argued that their results indicated something closer to a "fitter-get-richer" version of preferential attachment. They explained that central positions in their network were held by the "fittest" firms: the ones with the strongest stocks of technological capital. In this way, the value of a firm's technological capital was the underlying mechanism driving its degree centrality.

As in the cases of Gay and Dousset (2005) and Takeda et al. (2008), degree centrality is more appropriate to this dissertation than betweenness centrality. In Chapter 2, I discussed the work of von Hippel (1976, 1988) and his colleagues (Riggs & von Hippel, 1994; Spital, 1979) who described publicly employed scientists as the "locus" of scientific instrument innovation. These authors used the term "locus" to imply that scientists were both the origin of new product ideas and the most important players in a linear product development process. The scientists were not described as playing a brokerage role; instead, they were described as the "dominant" (Riggs & von Hippel, 1994; von Hippel, 1976) and the most influential players in the innovation process. I therefore consider degree centrality to be the appropriate network measure. For analytical purposes, Proposition 1 can therefore be restated as a hypothesis:

H1 Public research organizations have significantly greater average degree centrality than all other types of organizations in a scientific instrumentalities interactive learning network.

Here, I suggest that the findings of von Hippel and colleagues can be used to predict the relative position of certain actors within a scientific instrumentalities network. In Chapter 6, this hypothesis will be evaluated using a relatively simple network-based t-test.

Network composition: Symbiosis. More sophisticated multivariate network analyses have been used to identify the factors that influence an innovation network's structural composition. For example, Cantner and Graf (2006) performed network regressions on data about co-patenting in Jena, Germany. They found that two organizations were more likely to have cooperated on patents if those organizations conducted R&D in a common patent class and experienced some labour mobility, or movement of scientists, between them (Cantner & Graf, 2006). The results of Cantner and Graff's (2006) multivariate network analysis contribute to a broader literature of non-network multivariate studies. This literature has shown that certain interactive learning channels are more or less important for different types of organizations in different contexts (Arza, De Fuentes, Dutrénit, & Vazquez, 2015; Bekkers & Freitas, 2008; Cohen, Nelson, & Walsh, 2002; De Fuentes & Dutrénit, 2012; Dutrénit & Arza, 2010; Narin, Hamilton, & Olivastro, 1997). Thus, institutional context shapes the structural composition of an interactive learning network. Further, certain control variables are important for multivariate analyses of interactive learning, particularly organizational size (Cohen et al., 2002; Hanel & St-Pierre, 2006; Santoro & Chakrabarti, 2002), age (Eom & Lee, 2009; Giuliani & Arza, 2009), and absorptive capacities (Cohen et al., 2002; Fontana, Geuna, & Matt, 2006)—which are frequently measured as R&D intensity (Eom & Lee, 2009; Laursen & Salter, 2004; Torres, Dutrénit, Becerra, & Sampedro, 2011). A multivariate approach is needed to account for this range of factors that can influence network composition.

In another prominent example of multivariate network analysis, Sorenson et al. (2006) examined a U.S. patent citation network. They found that social and geographic proximity had a significant impact on moderately complex knowledge transfers among patent holders (Sorenson et al., 2006). Proximity—especially geographic proximity—is an extremely important variable in studies of interactive learning (Bishop, D'Este, & Neely, 2011; Broström, 2010; De Fuentes & Dutrénit, 2012; Laursen, Reichstein, & Salter, 2011). Filippetti and Savona (2017) explained that "geographic proximity has traditionally been considered the main determinant of UI interactions" (p. 2). However, in their research, Roman Martin and Jerker Moodysson (R. Martin, 2013; R. Martin & Moodysson, 2011a) demonstrated that the importance of geographic proximity on the structure of an innovation network depends upon an industry's underlying knowledge base. Distance is less important for "analytic" or science-based industries than it is for "synthetic" (i.e., engineering-based) or "symbolic" (i.e., art-based) ones (R. Martin, 2013; R. Martin & Moodysson, 2011a). Scholars continue to debate the importance of geographic proximity for certain innovation systems. Because scientific instrumentalities develop at the intersection of analytic and synthetic knowledge bases, it is not entirely clear how important geographic proximity might be for ocean science instrumentality innovation in Nova Scotia. It is clear, however, that geographic proximity should be included as a variable in my analysis.

For anyone familiar with multivariate analysis, the studies discussed above may appear to be very straight-forward. However, a distinct analytical approach is required when examining network structure/composition because network data violates two core assumptions of common statistical tests: network observations are not randomly sampled, nor are they independent of one another. Most network analysis techniques require data on a whole network rather than a network sample (Borgatti et al., 2013) because many network variables incorporate some measurement of the overall network composition. Such measures can vary considerably under different sampling conditions; so, network observations are not randomly sampled—they must be systematically collected. Furthermore, network analysis investigates sets of interdependent observations, and therefore cannot rely on standard statistical methods that assume independence of observations.

A common solution to this problem is the quadratic assignment procedure (QAP) (Hubert, 1987; Krackhardt, 1988; J. L. Martin, 1999). QAP is considered superior to ordinary linear regression for network analysis (Krackhardt, 1988). This re-sampling process takes observed data and randomly rearranges the rows and columns of a dependent variable matrix. The relational structure of the dependent matrix is preserved, but it is no longer related to the independent variable matrix because observations have been reassigned to different nodes. This approach can be used to create a collection of observations that could have occurred at random. Properties of the observed data can then be compared against the properties of several thousand random permutations. The result of QAP is a permutation distribution that allows network analysis software to evaluate the statistical significance of observations: calculating the percent of permutations that yield values greater or less than the observed values.

By adopting the QAP approach, it becomes possible to restate theoretical propositions 2 and 3 as hypotheses. Proposition 2 relates to the nature of interactive learning between PROs and private companies in a scientific instrumentalities innovation system. I proposed that PRO-company relations should involve multiple channels of interactive learning. In network terms, this means the relations should be multiplex—they should incorporate multiple types of edges. Only a few recent studies of science-industry networks have accounted for multiple channels (e.g., Arza & Carattoli, 2017; Calignano & Fitjar, 2017; Calignano, Fitjar, & Kogler, 2018; Martin & Rypestøl, 2017; Xu, Wu, Minshall, & Zhou, 2017). I also proposed that PRO-company interactions should involve bidirectional learning—two-way knowledge flows based on interactive learning channels operating in both directions. One recent study of science-industry interaction (Arza & Carattoli, 2017) explicitly investigated bidirectionality via an aggregate "bidirectional channel" and found that it provided positive knowledge benefits to PROs in Argentina.

Using these concepts, I hypothesize that:

H2 Within a scientific instrumentalities interactive learning network, relations between PROs and private companies are multiplex and bidirectional.

Network composition: Channels of interaction. We know that composition of interaction channels in an innovation system will vary according to contextual and organizational factors. In proposition 3, I argued that the most important channels of interactive learning for scientific instrumentality innovation involve the provision and acquisition of capital equipment and technical services. It is possible to identify the most important edges in a network using a measure of edge betweenness developed by Girvan and Newman (2002). This measure is similar to betweenness centrality, except that it applies to edges rather than nodes. It assesses the importance of an edge based on the number of times that edge lies on the shortest path between any two nodes in the network (Borgatti et al., 2013; L. C. Freeman, 1977; Girvan & Newman, 2002). Based on this measure of edge importance, I can restate Proposition 3 as the following hypothesis:

H3 The presence of a capital equipment and technical services interaction significantly and positively predicts the edge betweenness of a relationship in a scientific instrumentalities interactive learning network.

Hypotheses 2 and 3 can both be evaluated using QAP adaptations of common multivariate tests. These hypotheses address the factors that influence the relational composition of a scientific instrumentality innovation system. The following section develops one further hypothesis about the structure of the whole system.

Network dynamics: Fragmentation. Glückler and Doreian (2016) have noted that in the field of economic geography—which intersects with innovation studies—network analysis has been used mostly to examine individual actors or dyads of actors, with very little attention to the evolution and composition of whole networks. This is the third way—the most sophisticated, yet underutilized way—that innovation scholars have used network analysis. In one prominent example, Giuliani (2013) applied stochastic actor-oriented models to longitudinal data on a wine industry network in Chile. She found that over time new network ties were formed when actors reciprocated contact from other actors and/or closed an open triad of relations. In graph theory, these network dynamics are referred to as reciprocity and transitive closure. Interestingly, Giuliani (2013) found that these network dynamics did not apply for firms with weak knowledge bases; those firms remained in the network periphery over time.

In Chapter 3, I concluded with a proposition about the structural dynamics of a scientific instrumentalities innovation system such as the ocean science instrumentalities system in Nova Scotia. I suggested that such innovation systems may be structurally dependent upon PROs as anchor tenants. In graph theory, the structural dependence of a network on certain nodes is referred to as "robustness" (Barabási, 2013; Callaway, Newman, Strogatz, & Watts, 2000). A network's robustness is a function of how well it remains connected when individual nodes or edges are removed (Borgatti et al., 2013). A network is said to be highly robust when a large number of nodes or edges need to be removed before the network begins to fragment into many small components (Borgatti et al., 2013). As I discussed in Chapter 3, robustness has only been qualitatively explored in innovation studies. Some have suggested that Silicon Valley's present-day innovation system is highly susceptible—not robust—to the loss of venture capital firms (Ferrary & Granovetter, 2009). Others have suggested that Boston's biotech innovation system was not robust to the removal of PROs in the late 1980s (Powell et al., 2012).

The dynamic effect underlying network robustness is fragmentation. In a network with no fragmentation, all nodes are members of one component—no individual nodes are isolated from the group, and no small groups of nodes are disconnected from the main component. When there is no fragmentation present, any node in a network can reach any other node by working through its neighbours. Stephen Borgatti (2006) identified several ways to measure network fragmentation. For all these measures, a network becomes fully fragmented (F = 1) when all nodes are disconnected from one another. Fragmentation measures differ in the ways that they account for degrees of fragmentation. The simplest approach is to count the number of components—or groups of nodes—in a network and then divide by the total number of nodes. But for the states where F is somewhere between 0 and 1, fragmentation measures should be adjusted to account for the structure of the network (Borgatti, 2006). Using this measurement technique, Calignano, Fitjar, and Kogler (2018) observed that the aerospace cluster in Apulia, Italy was highly fragmented in a static sense (i.e., the whole network's degree of fragmentation was measured at two separate points in time, without modelling perturbations between time periods).

Borgatti (2006) argues that we should go further than measuring the fragmentation as a static state. He suggests that we should account for the impact on network structure that occurs when nodes are lost: the loss of a well-positioned node, one with high degree or betweenness centrality, for example, can have greater implications for the functioning of a network than the loss of a peripheral node (Borgatti, 2006). To calculate the impact of node loss on network structure, Borgatti (2006) considers the reciprocal distance between nodes. In other words, he measures the degree to which any pair of nodes in a network can reach one another via connections with their neighbours. He calls this "distance weighted fragmentation" (${}^{D}F$) (Borgatti, 2006). In practical terms, reachability is the number of edges that a piece of knowledge must traverse to find its way from one organization to another in an interactive learning network. After incorporating reachability into a measure of fragmentation, Borgatti (2006) gives us this equation:

$$^{D}F = 1 - \frac{2\sum_{i>j}\frac{1}{d_{ij}}}{n(n-1)}$$

Here, *i* and *j* are nodes in a network, d_{ij} is the geodesic distance between those nodes, and *n* is the total number of nodes in the network. The numerator incorporates a reciprocal of the distance between nodes. For nodes that cannot reach one another—in other words, distance is infinite—the reciprocal distance is zero. Distance-weighted fragmentation has a lower limit of zero when every pair of nodes is adjacent to every other pair. It has an upper limit where every node is an isolate. For my purposes, distance-weighted fragmentation is useful because it can be a node-level measure: the change in ^{D}F of the network can be calculated after removal of any individual node. The concept of distance-weighted fragmentation allows me to restate my fourth theoretical proposition as a hypothesis:

H4 Removing individual PROs from a scientific instrumentalities interactive learning network results in significantly greater distance-weighted fragmentation than removing other types of organizations.

Hypothesis 4 is relatively simple to test using readily available network analysis software. More sophisticated applications of robustness analysis could be used to compare different error and attack scenarios, including the cascading effects of successive node loss (Barabási, 2013). As Albert Barabasi explains, “in general, removing a fraction of nodes has limited impact on a network’s integrity. Once the number of removed nodes reaches a critical threshold, the network abruptly breaks into disconnected components” (Barabási, 2013, p. 8). In my final chapter I will discuss the opportunities to develop new tools for more sophisticated analysis of multi-node error and attack scenarios. Here, my goal is to introduce a relatively simple approach to quantitative analysis of a theoretically and contextually important network dynamic.

Above I have introduced key analytical concepts from network science and restated my four theoretical propositions as hypotheses. These hypotheses include measurement concepts from network analysis. The next step before an analysis an be conducted is to stipulate and clearly specify network boundaries. This is the purpose of the following section.

Boundary Specification

At the beginning of this chapter, I engaged with the concept of institutions within innovation systems. Now, having developed concepts from network science, I revisit the idea of an innovation system as an institutional field and develop the final piece of my analytical framework: the boundary specification. Boundary specification is an issue in studies of regional innovation systems—where the debate is about regional scale (Doloreux & Parto, 2005) and in the field of network analysis—where the debate is about network ontology (Laumann, Marsden, & Prensky, 1983). In this section, I use theory from innovation systems and network science to define the boundary around Nova Scotia's ocean science instrumentality innovation system.

Edquist and Johnson (1997) have suggested that the boundaries around an innovation system are "always" (p. 60) or at least "normally" (p. 40) defined in terms of institutions—i.e., the playing field is delineated by the rules of the game. In other words, an innovation system can be described as an institutional field or organizational environment in which interactive learning takes place. The boundaries of an innovation system typically correspond with national borders (Meeus & Oerlemans, 2005b), regional economies (Gertler, 2010), or socio-technical regimes (Fuenfschilling & Truffer, 2014). Some believe that socio-technical regimes correspond with product-based industry classifications—industries or sectors—but this can be a problematic oversimplification. Whether the context for an innovation system is geo-political, socio-economic, or socio-technical, the institutional rules within the system—the cultural norms or laws and regulations (North, 1990)—are relatively homogenous. These rules differ from one institutional field to the next, but the institutional fields also intersect one-another (Castellacci, 2009; C. W. Freeman, 2002), particularly when conceived as a “regional, sectoral innovation system” (Cooke, 2002). Given the nested and overlapping nature of institutional fields, the boundaries of an innovation system are always open (Belussi, Sammarra, & Sedita, 2010), semi-coherent (Fuenfschilling & Truffer, 2014), and fixed only for analytical purposes. David Doloreux and Saeed Parto (2005) have labelled boundary specification as the “unit of analysis” problem in studies of regional innovation systems. It is the problem of determining whether the innovation system boundaries align with a city, metropolitan region, local district, sub-national region, and so on. Doloreux and Parto (2005) considered this to be one of the major unresolved issues in the field. They proposed that proper deployment of institutions—the “key variable” in regional innovation systems (Doloreux & Parto, 2005)—helps resolve this issue while at the same time suggesting that “there is a danger of getting ‘lost in the woods’ while searching for the institutional component” (Doloreux & Parto, 2005, p. 146).

I propose that network science can help guide the way. Just as boundary specification is a central issue in the study of innovation systems, it is also a central issue in network analysis (Laumann et al., 1983). Edward Lauman, Peter Marsden, and David

Prensky (1983) wrote about this problem and distinguished between realist and nominalist approaches to network boundary specification.[21] The realist approach assumes that a network is a well-defined social entity that “exists as a collectively shared subjective awareness of all, or at least most, of the actors who are members” (Laumann et al., 1983, p. 21). From this perspective, researchers often ask network actors to define their own network boundary. The realist approach also often involves the use of analytical methods to identify network boundaries based on the contours of actors’ relations. Alternatively, under the nominalist approach, network boundaries do not need to be perceived by the actors because they are defined by the researcher. The researcher defines nominalist network boundaries “by imposing an a priori conceptual framework that serves an analytic or theoretical purpose for a particular project” (Knoke & Yang, 2008, p. 16). This nominalist approach is consistent with Edquist’s assertion that the boundary for an innovation system “depends on the object of study” (Edquist, 1997, p. 12). For this reason, I follow a nominalist approach to boundary specification. I specify a network boundary by imposing an innovation systems conceptual framework, allowing me to establish a set of inclusion rules that define the network boundary (Laumann et al., 1983).

Laumann et al. (1983) outline four nominalist strategies for boundary specification. Two of these strategies align with the innovation systems conceptual framework. The first and most obvious way to specify the boundaries of an innovation system network is to use a “nodal attributes” strategy (Laumann et al., 1983) which restricts the network to

[21] Note that Laumann et al. (1983) use the concepts “nominalist” and “realist” differently than other scholars (cf. Burrell & Morgan, 1979).

certain kinds of nodes. Laumann et al. (1983) present the work of Galaskiewicz (1979a, 1979b) as an exemplar of this strategy. Galaskiewicz (1979a, 1979b) used a combination of geographic and industry criterion to bound his study of inter-organizational networks in a small city (Galaskiewicz, 1979a, 1979b). On the surface, this boundary setting approach appears perfectly suited to the study of a regional-sectoral innovation system. However, the nodal attributes strategy is only appropriate for the geographic boundary of my system, not the "industry" boundary. It is quite simple to set inclusion criteria based on an organization's geographic location. The next chapter will describe how my interviews with five ocean science and technology experts in Halifax confirmed that a provincial boundary—Nova Scotia—was more appropriate for this study than a sub-provincial or ultra-provincial boundary[22]. A different strategy is needed to establish a sectoral boundary.

In previous chapters I have outlined the sectoral context of this study as the field of ocean science instrumentalities which includes both scientific instruments and scientific techniques. Using the term "instrumentalities," de Solla Price (1984) argued that communities of scientists and technicians that collaborate on scientific instrumentality innovation are "bound together in their invisible colleges" (p. 15). In this way, the scientific instrumentalities sector defies—or "crosses"—the boundary between science and industry (Kaufmann & Tödtling, 2001). The sector does not conform to any standard

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[22] Some readers might argue that the appropriate boundaries for any study of ocean science and technology should correspond with the geography of the ocean. For example, one might argue that my study should be focused on a North Atlantic geography. However, the ocean does not impose institutional rules the way that provincial or national governments do.

industry classification system. Above I suggest that the field of ocean science crosses traditional scientific boundaries because it encompasses the full range of chemical, biological and physical scientific investigations of the ocean and its contents. The field of ocean science instrumentalities is a subset of a scientific instruments sector and a subset of an ocean technologies sector. However, given the lack of coherence in defining ocean technologies (see Chapter 3), it is not possible to rely upon "a collectively shared subjective awareness" (Laumann et al., 1983, p. 21) of this sector. There are nominalist grounds by which to establish a sectoral network boundary, but not realist grounds by which the actors will naturally identify a boundary themselves. They may identify as being part of an ocean technology industry, not an ocean science instrumentality sector.

Above, I suggest that the term "sector" should not always be used interchangeably with the concept of a socio-technical regime (Fuenfschilling & Truffer, 2014) when it comes to specifying an ocean science instrumentalities system boundary because the terms sector and industry both tend to be applied in a way that separates public and private sector organizations. Sectors are often defined based upon standard product or industry classifications (e.g., NAICS, SIC), which separate public organizations from goods producing firms. Indeed, the North American Industry Classification System (NAICS) makes this separation at the first-digit level (Statistics Canada, 2012). However, a "socio-technical" or "technological" regime (Breschi, Malerba, & Orsenigo, 2000; Malerba & Orsenigo, 1996, 1997; Nelson & Winter, 1982) is a broader concept that represents an institutional field (Breschi & Malerba, 1997; Fuenfschilling & Truffer, 2014) in which "a system of *firms* [emphasis added]" (Breschi & Malerba, 1997, p. 131) are connected

> through processes of interaction and cooperation in artefact-technology development and through processes of competition and selection in innovative and market activities. (Breschi & Malerba, 1997, p. 131)

A socio-technical regime can therefore be identified based on its formal institutional boundary, such as the unique regulatory environment found in financial services sectors, or based on the interactions that are shaped by a combination of formal and informal institutions. Since the ocean science instrumentalities sector does not have a readily identifiable formal institutional boundary, the best approach is to identify this institutional field by way of the activities that it shapes. Returning to North's (1990) sports metaphor, my approach is like finding the limits of a football field by observing the players in action.

Fixing the sectoral system boundary therefore requires a particular boundary specification strategy. The "event or activity" strategy from network science (Laumann et al., 1983) involves setting network inclusion rules based on participation in a certain kind of activity. Laumann et al. (1983) present the work of Crane (1972) and Burt (1978) on scientific invisible colleges as exemplars of this boundary specification strategy. In this research, members of an invisible college network were "identified on the basis of their interest in a particular field of research, irrespective of their disciplinary label" (p. 28). This boundary specification strategy can be applied to a scientific instrumentalities sector in a similar way. The boundary can be established on the basis of an organization's engagement with a particular field of scientific instrumentalities, regardless of any other industry or disciplinary labels. In this dissertation, the sectoral boundary therefore includes organizations that have engaged in inter-organizational interactive learning for the purposes of using and/or producing ocean science instrumentalities. To ensure that the network captures present-day context, a temporal filter of the past five years will also be applied to this activity-based inclusion rule. Gilsing et al. (2008) and Casper (2007) both provide rationale for a five-year research window when studying innovation networks.

The preceding discussion has established rules by which a particular regional-sectoral innovation system can be conceived as a network for analytical purposes. Participants in this network can be identified on the basis of their geographic presence—the regional boundary—and their interactive learning activities in a particular technological regime during a particular period of time—the sectoral boundary. The interactive learning network that I examine therefore includes organizations that:

(1) operate in Nova Scotia; and
(2) (a) interacted with external organizations in some way,
(b) for the purposes of using and/or producing ocean science instrumentalities,
(c) in the past 5 years.

This inclusion rule mixes together nodal attribute and activity-based boundary specification strategies indicating which organizations will be included as nodes in the network analysis of this innovation system. Note that the rule was carefully constructed so that neither public nor private organizations would be excluded.

Laumann et al. (1983) suggest that mixing multiple boundary definitions can lead to "theoretically elegant definitions of membership" (p. 24), but researchers should be careful to ensure that they do not inadvertently fix the network features they intend to investigate—either the nodes or edges (Laumann et al., 1983). For my purposes, the types of organizations and the types of relations must both be "free to vary" (Laumann et al., 1983, p. 20). The hypotheses developed earlier in this chapter position network relations and relational structures as dependent variables. Indeed, because interactive learning is at the theoretical core of the innovation systems approach (Lundvall, 2013), the default focus of any innovation system network analysis should be on the learning interactions. The inclusion rule above allows for the identification of organizations based partly on their learning interactions. However, the network boundary must also be specified in a way that allows these interactions to vary empirically.

One final boundary specification rule is therefore needed to specify the range of theoretically-appropriate relations that will be included in the network analysis of this innovation system. This may appear unusual to those who study innovation systems, but network analysis requires inclusion rules for both the actors in the network and the types of relations in the network (Laumann et al., 1983). Such rules are easily drawn from my earlier theoretical discussion of interactive learning. My typology of interactive learning relationships (Table 1) provides a comprehensive list of the seven kinds of relationships that should be included in this network. Any two nodes in the network could be interacting in one or more ways, or they might not be interacting in any of these ways at all. The network boundary does not include relationships that fall outside this channels of interactive learning framework. For example, two organizations might both belong to their local chamber of commerce, but this common membership would not be considered an interactive learning relationship.

Summary of the Analytical Framework

In this chapter, I built upon the theory and context introduced earlier in the dissertation to establish an analytical framework. The analytical framework uses constructs from network science to frame the analysis of an innovation system (see the Glossary of Terms that follows Chapter 7). In this chapter, I emphasized three important analytical moves. These are illustrated in Figure 5. First, I differentiated between key components of an innovation system: organizations, learning interactions, and the institutional environment. Then I framed the contents of an innovation system—the organizations and their interactions—as a network (note that Figure 5 contains a simplified three-node network). Key methods and measures were introduced related to the analysis of network positions, network composition, and network dynamics. These concepts were used to reformulate Propositions 1 through 4 as hypotheses for testing in a network analysis (see Figure 5 and Table 5). Finally, I developed inclusion rules for the organizations and relations that fall within a theoretically-justified network boundary. The network boundary includes organizations that operate in Nova Scotia and interacted with external organizations through the five channels of interactive learning for the purposes of using or producing ocean science instruments or techniques in the past five years. The analytical framework developed in this chapter provides the necessary foundation for data collection in Chapter 5.

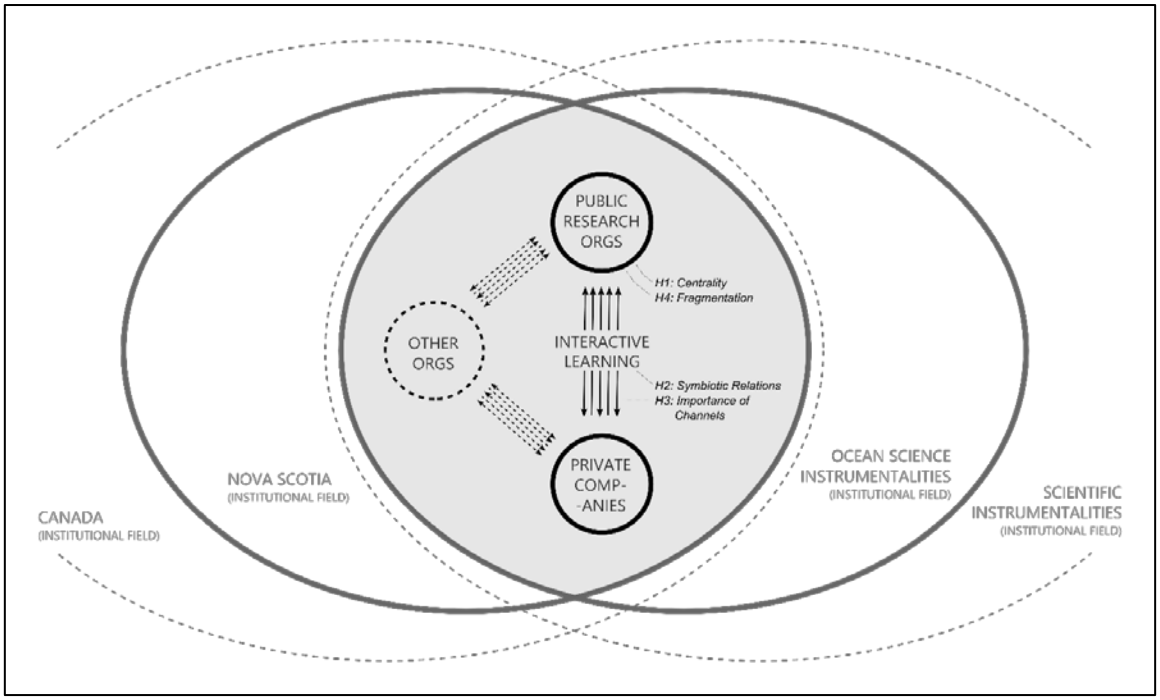

Figure 5. Analytical framework for understanding the importance of public organizations for ocean science instrumentality innovation in Nova Scotia, Canada. Author's own work.

Table 5

Restating Theoretical Propositions as Hypotheses for Network Analysis

Theoretical Propositions		Hypotheses	
P1	Public research organizations are the most important actors in a scientific instrumentality innovation system.	H1	Public research organizations have significantly greater average degree centrality than all other types of organizations in a scientific instrumentalities interactive learning network.
P2	The interactive learning between PROs and scientific instrumentality companies involves multiple channels and is bidirectional.	H2	Within a scientific instrumentalities interactive learning network, relations between PROs and private companies are multiplex and bidirectional.
P3	The most important interactive learning channels for scientific instrumentality innovation involve the provision and acquisition of capital equipment and technical services.	H3	The presence of a capital equipment and technical services interaction significantly and positively predicts the edge betweenness of a relationship in a scientific instrumentalities interactive learning network.
P4	A scientific instrumentalities innovation system is more susceptible to the loss of public research organizations than to the loss of other types of organizations.	H4	Removing individual PROs from a scientific instrumentalities interactive learning network results in significantly greater distance-weighted fragmentation than removing other types of organizations.

Chapter 5: Method

For this study, I collected data on interorganizational interactive learning in the field of ocean science instrumentalities in the province of Nova Scotia, Canada. This chapter describes the methods I used to collect a quality network dataset that includes both public and private organizations. I collected data from July 2016 to February 2017 using a “fixed list” approach (Doreian & Woodard, 1992) and a “personal-network research design” (Borgatti et al., 2013). Interviews with five system-level experts (see Appendix B) yielded a list of 27 organizations that met the boundary specification criteria. I interviewed key informants from public and private organizations using the same structured questionnaire (Appendix C). When all interviews were complete, I aggregated the responses into a whole network dataset containing the variables that are described near the end of this chapter. I conclude this chapter with a description of the steps that I took to ensure validity and reliability of the data.

Research Design

Fixed list approach. In Chapter 4, I developed a nominalist boundary specification (Laumann et al., 1983) for the ocean science instrumentalities interactive learning network in Nova Scotia (hereafter called, “the network”). Now I will describe the specific technique that I used to identify the nodes and edges that fall within this network boundary, a technique commonly referred to as a “fixed list” approach (Doreian & Woodard, 1992). For the purposes of this study, the fixed list approach is more appropriate than the alternative— an “expanding set” approach (Doreian & Woodard, 1992). The expanding set approach is often simply referred to as snowball selection or snowball sampling (Doreian & Woodard, 1992). The fixed list approach has practical advantages over the snowball approach; it is also the appropriate choice for research focused on the relations and relational structures of a network.

A fixed list approach involves setting an *a priori* list of network nodes and then collecting data on the presence or absence of relations between those nodes. It means that the network nodes are fixed, but the relations between them are variable. This fixed list approach is consistent with the boundary specification rules developed in Chapter 4 which were designed so that organizational legal forms can vary and, more importantly, the network can include a range of interactive learning relationships between dyads—or, for some dyads, no relations at all.

Laumann et al. (1983) suggest that snowball sampling should not be used for research that investigates certain relational structures of networks, such as those investigated in this study. Indeed, a snowball selection approach would not allow the same focus on interactive learning relations and structures. Using snowball selection means following chains of relations to identify previously latent nodes. After the first wave of snowball sampling, the relations that have been sampled become fixed. These relations are then used to identify and sample additional nodes in subsequent snowball waves. This systematic error can culminate in tautological results; as Lauman et al. (1983) explain, “it is scarcely informative to learn that a network constructed by a snowball sampling procedure is well connected or ‘integrated’” (p. 22). Using snowball selection would have introduced such a tautology in this study because the robustness and fragmentation dynamics of a network depend upon its connectedness. Any network will appear more robust if constructed through snowball selection rather than a fixed list approach.

There are also practical advantages to using a fixed list approach. The fixed list approach avoids potential errors associated with the data cleaning stage of snowball selection (Doreian & Woodard, 1992). It allows for the use of a roster recall interview technique providing respondents with a pre-defined list of other organizations in the network which limits respondent biases (Borgatti et al., 2013; Doreian & Woodard, 1992). Finally, the fixed list approach is much less resource intensive than the snowball selection approach (Doreian & Woodard, 1992) because it focuses data collection resources on sampling the core of a network.

As Patrick Doreian and Katherine Woodard (1992) explain, “one of the advantages of the fixed sample design is that it concentrates on the core” (p. 224). Through their research on a regional network of mental health service organizations, Doreian and Woodard (1992) demonstrate that a fixed list approach captures the core of a network, but fails to capture its “context”—the periphery. A network can be said to have core-periphery structure when it contains a core group of nodes that are densely interconnected and a peripheral set of nodes that are loosely connected to the core and relatively disconnected from one another. Core-periphery structures are common and well-documented in research on innovation networks (Cattani & Ferriani, 2008; Giuliani, 2013; Giuliani & Bell, 2005; Kudic, Ehrenfeld, & Pusch, 2015; Rank, Rank, & Wald, 2006; G. Walker, Kogut, & Shan, 1997). Some studies suggest that isolated or loosely connected nodes in a network periphery could be important for creativity and innovation (Cattani & Ferriani, 2008; Kudic et al., 2015). Generally however, positions in the network core are seen as more valuable for innovation because they provide better access to knowledge in the network (Giuliani, 2013; Giuliani & Bell, 2005; Kudic et al., 2015;

Rank et al., 2006). The core of an innovation network includes “…key members of the community, including many who act as network coordinators and have developed dense connections between themselves” (Cattani & Ferriani, 2008, p. 826). This idea is consistent with research suggesting that organizations in the core of an innovation network have significantly greater absorptive capacities than those in the periphery (Giuliani & Bell, 2005). Furthermore, several studies have shown that innovation networks develop core-periphery structures over time and these structures then become stable and relatively fixed (Giuliani, 2013; Kudic et al., 2015; Rank et al., 2006; G. Walker et al., 1997). This research therefore suggests that the core of an innovation network may be the most dynamic site for interactive learning.

Following on this research, my study focuses on the core network of ocean science instrumentality innovation in Nova Scotia. Because the core network is the most highly connected portion of a wider network, all the most highly connected nodes will be found within it. Remember, hypothesis 1 states that PROs are the most highly connected nodes. Also, because the core is densely connected, it is the most robust portion of any wider network. Hypothesis 4 states that the removal of PROs results in greater fragmentation than the removal of companies. In other words, the network will be more robust in the face of lost companies than lost PROs. The core network is therefore an appropriate context for investigating the hypotheses in this study.

The disadvantage of focusing on the core network is that any peripheral nodes are excluded which may introduce bias in certain network measures. However, Doreian and Woodard (1992) found that even betweenness centrality, which measures a node’s position with respect to all other nodes in a network, was strongly correlated (R^2 = 0.57

and 0.89) for two studies where they were able to compare a fixed list approach—a core network with no periphery—to a snowball selection approach—a core network plus periphery. They also found that a fixed list approach “underreports the extent to which the agencies in the fixed list belong to the core” (p. 225). In other words, focusing on a core network does have an effect on network measures, but the effect is an understatement rather than a misstatement of the core nodes’ centrality in the network. Overall, a fixed list approach is preferable to a snowball selection approach because it avoids a potential tautology, introduces fewer chances for error, is less resource intensive, and identifies a core network, which is the appropriate context for testing the hypotheses in this study.

Construction of the fixed list. I used a “system-level informant free-list” technique (Borgatti et al., 2013) to identify the fixed list of organizations in the network. Based on media reports, attendance at sector events, and personal networks, I identified all individuals based in Halifax whose work responsibilities included understanding and supporting the ocean science and technology sector. These five individuals are hereafter called the system experts. Three of these individuals held industry policy roles—one in a federal organization and two in different provincial agencies—and two held sector support roles in separate not-for-profit organizations. I invited these individuals to participate in an interview and presented them with a research consent agreement (see Appendix D). I then conducted structured interviews with these individuals using a touch screen computer running the network data collection platform EgoWeb 2.0 . Screenshots of the full interview instrument can be found in Appendix B. At the outset of each interview, ocean science instrumentalities were defined on-screen and read aloud as:

- Scientific instruments (such as hydrophones that can be used for collecting data on marine life); and
- Research techniques (such as methods for processing data from those hydrophones).
- But this does not include new marketing or organizational techniques (such as the way hydrophones are packaged for sale or the way human resources are managed).

The system experts were then asked to identify organizations involved in using and producing ocean science instrumentalities in this region. This was a free-recall task: the experts each independently named relevant organizations, except for one expert who engaged a colleague in helping to establish a complete list. Following on the best practices in network data collection, I used elicitation prompts to ensure that a range of organizations were identified (Brewer, 2000). The experts were prompted to include academic, private-sector, government[23], and not-for-profit organizations. The concept of a kind-of-activity unit was described on screen and read aloud as follows:

> For the purposes of this study, an organization is not necessarily a standalone legal entity. In many cases, the parent organization (e.g., Saint Mary's University) is less relevant to this study than a particular department, unit, or division (e.g., the Sobey School of Business). An operating unit can be considered an “organization” if it engages in one kind of activity and has some decision-making autonomy (OECD, 2005).

It can be challenging to identify appropriate regional innovation system boundaries in Canadian contexts (Holbrook & Wolfe, 2000). Particularly in Atlantic Canada, one must consider whether the maritime provinces constitute one region or three regions

[23] In all interviews, I used the colloquial label “government” and avoided engaging respondents in a complex theoretical discussion about the public/private distinction.

(Holbrook & Wolfe, 2000). There is also increasing emphasis on major cities as the appropriate contexts for regional innovation system research in Canada (Wolfe, 2014). To this end, the five experts were given latitude to define the regional boundary based on their understandings of the innovation system context. The experts were not directly asked to identify the region, but rather were asked to name appropriate organizations "in this region." All five experts named a key organization outside the city of Halifax. Four experts restricted their lists to organizations in Nova Scotia. The fifth expert included organizations located elsewhere in Atlantic Canada, including organizations in New Brunswick and Newfoundland and Labrador. Based on the majority opinion of the experts, the innovation system's regional boundary was confirmed to be the Province of Nova Scotia.

Organizations were included in the fixed list of network nodes if they were named by the majority of experts. In other words, all those organizations that were named by three or more experts were included in the fixed list (see Table 6). All five experts independently named the same 11 organizations. An additional six organizations were named by four experts, and 10 were named by three experts. In total, the five experts named 126 organizations: 60 public organizations and 66 private companies. All academic, government, and not-for-profit organizations that were named were classified as public organizations (per the criteria from Perry & Rainey, 1988). The first four experts named between 25 and 40 organizations each, while the fifth expert named 92. The fifth expert named disproportionately more organizations because they defined the regional boundary differently.

Table 6

Levels of Agreement Among Experts

Level of Expert Agreement	Organizations
No agreement (One expert: 20%)	72
2 Experts Agree (40% agreement)	27
3 Experts Agree (60%)	10
4 Experts Agree (80%)	6
All 5 Experts Agree (100%)	11
Total Organizations Named	126

Table 7

Number of Ocean Science Instrumentality Organizations Identified by Experts

Expert	No. of Orgs.	Agreement with other Experts		
		2 or more others	1 other	No others
#1	32	18	6	8
#2	25	19	5	1
#3	28	17	7	4
#4	40	19	15	6
#5	92	23	16	53
Total	126	27	27	72

Note. Totals indicate the number of unique organizations named.

There were important differences in the ways that the experts spoke about Dalhousie University and the Nova Scotia Community College. One expert named Dalhousie University as a key organization, but not all kind-of-activity units (KAUs) within the university engage in using or producing ocean science instrumentalities. The four other experts all named the university's Oceanography Department and three of the experts named another specific KAU that remains confidential in this study. I gave the fifth expert the benefit of the doubt; I assumed that this expert would have named both of these units, if he had been able to name specific KAUs. The Oceanography Department is included among those organizations named by all five experts and the other KAU is included among those organizations named by four experts.

Similarly, three experts named the Nova Scotia Community College (NSCC) as a key organization, but were unable to identify specific KAUs in the college that engage in using or producing ocean science instrumentalities. The other two experts could identify specific KAUs and they both named the Applied Geomatics Research Group at Annapolis Valley Campus, and the ocean science and technology operations at the NSCC Waterfront Campus—one expert called this the "waterfront program" and the other called it the "advanced diploma program." There are indeed two closely-related KAUs at the NSCC Waterfront Campus that are engaged in using and producing ocean science instrumentalities: the NSCC Advanced Diploma in Ocean Technologies is a training program for ocean technologists and the NSCC Applied Oceans Research Group is a research laboratory partly funded by the Natural Sciences and Engineering Research Council of Canada. These three KAUs at NSCC were therefore treated as if they would have been named by the other experts, if those experts had been able to name specific KAUs within the college. However, three other KAUs at NSCC were named by expert 4 but not by any other expert. Since these were only named by one expert, they were not included in the fixed list.

A different issue arose with the Bedford Institute of Oceanography (BIO). All five experts identified BIO as a relevant organization. However, BIO is technically a Government of Canada campus: it consists of buildings owned by the Department of Public Works and Government Services. Multiple public organizations are tenants at the site. The Bedford Institute of Oceanography is a collection of buildings, not a legal organization or a KAU. The KAUs present at BIO are regional divisions of two federal departments: the Department of Fisheries and Oceans (DFO) and the Geological Survey of Canada Atlantic—a KAU of Natural Resources Canada (NRCan). These were both included on the fixed list as BIO-DFO and BIO-NRCan.

The fixed list did not include organizations that were named by only one or two of the experts. Seventy-eight organizations were named by only one of the five experts—the other four experts did not identify these organizations. This included 53 organizations that were named only by Expert 5—58% of the organizations named by this expert. This expert named 23 organizations outside of Nova Scotia, 15 organizations in other sectors such as shipbuilding and offshore energy, and 15 public organizations that are not involved in using or producing scientific instruments.

An additional 27 organizations were named by only two experts—the other three experts did not identify these organizations. This number includes four units of Dalhousie University and three campuses of NSCC that were each only named by one expert, but treated as if they had been named by two, per the discussion above. This number also includes four non-research public organizations and one industry association that all clearly support the sector, but are not involved in using or producing scientific instrumentalities. Four of these were the workplaces of the experts, but interestingly, none of the experts identified his or her own organization as being qualified to participate in the study.

In short, there were 99 organizations mentioned during individual expert interviews that did not meet the threshold for inclusion on the fixed list[24]; the majority of experts did not identify these organizations. There are three potential reasons why an organization may have been named by only a minority of experts. First, one or more experts may have forgotten to name an organization. However, experts were selected based on their specialized knowledge of the ocean science and technology sector, they knew in advance that the interview would be focused on identifying relevant organizations, and elicitation prompts were used during the expert interviews to reduce the risk of forgetting (Brewer, 2000). The second possibility is that a minority of experts mistakenly named organizations that do not meet the inclusion criteria. This clearly occurred in several examples above, and in the case of Expert 5 using broader regional inclusion criteria than the other experts. It is not appropriate to include such organizations in this study because doing so would introduce false-positive node inclusion errors (Wang, Shi, McFarland, & Leskovec, 2012). A third possibility is that some organizations named by only a minority of experts do meet the inclusion criteria, but are peripheral to the network. Peripheral organizations might be new entrants to the network and/or they might be relatively less engaged in interactive learning about scientific instrumentalities in Nova Scotia. It is plausible that three or four experts might have been unaware of organizations in the loosely-connected periphery of the network. If this is the case, excluding those organizations from the study is consistent with a focus on the core of the network.

[24] Fifty-four of these were private companies and forty-five were public organizations.

To test my fixed list approach, I conducted interviews with five of the organizations that were excluded from the list. In these interviews, I confirmed that four of these organizations did not meet the boundary specification criteria developed in Chapter 4. The fifth was the Bras d'Or Institute, a small research unit with three full-time equivalent employees at Cape Breton University (CBU). The Bras d'Or Institute is physically located within the Verschuren Centre for Sustainability at CBU. The Verschuren Centre was included in the fixed list because it was named by three experts, while the Bras d'Or Institute was not—it was only named by two experts. Overall, these five interviews supported the argument that the organizations named by a minority of experts either do not fall within the network boundary specification or are peripheral actors in the network.

Data Collection

I identified key informants for all 27 organizations on the fixed list. The key informants were either the head of the organization (e.g., President, CEO, Executive Director) or a vice-head with sufficient knowledge of the organization's research and development activities (e.g., Vice President, Director). These individuals were invited to participate in an interview and presented with a research consent agreement (see Appendix E) based on the best practices template developed by Borgatti and Molina (2005). This consent agreement was reviewed and approved by the research ethics boards at both Saint Mary's University and Acadia University (see Appendix F). The consent agreements for expert interviews (Appendix D) and organizational key informant interviews (Appendix E) were similar in form. They followed a standard format, and included additional detail on the nature of network research and the risks of participating in such research, as suggested by Borgatti and Molina (2005) and Borgatti et al. (2013). With respect to confidentiality, the consent agreement specified that

> All data obtained from private sector companies will be kept confidential and will only be reported in an aggregate format (by reporting only combined statistics and by representing all private companies using one common colour/shape on network diagrams). No one other than the primary investigator and supervisor listed above will have access to the data about individual interviewees and the data about private companies. Data about public and not-for-profit organizations will be treated as public-record (i.e., not confidential), except where relationships with private sector companies are noted. To protect the strategic interests of private companies, this data will remain confidential. (Informed Consent Agreement 2—see Appendix E)

The consent agreement included a sample network graph which was used at the outset of each interview to explain the risk that private sector organizations may be identifiable in the research outputs. Given sufficient knowledge of the research context, an informed reader may be able to infer the names of particular network participants from their relations or positions on a network graph (Borgatti et al., 2013). This consent agreement was signed by all participants.

I opted to perform all interviews face-to-face. To that end, two interviews were conducted via Skype and the remainder were conducted in-person at the respondents' offices. Face-to-face interviews are the most effective approach to collecting network data (Borgatti et al., 2013). The lower response rate from survey approaches tends to introduce non-response bias in network studies, but this can be addressed by establishing rapport in face-to-face interviews (Borgatti et al., 2013). Self-completion surveys are also limited because the researcher is unable to improve data collection through prompts and probes (Bryman, Bell, Mills, & Yue, 2011). Conversely, face-to-face interviews allow the researcher to ensure clarity and encourage completion through prompts (Bryman et al., 2011). In short, face-to-face interviews improve network data collection by increasing rapport and allowing greater elicitation of network data (Borgatti et al., 2013).

I conducted face-to-face interviews with key informants from 25 of the 27 organizations on the fixed list. Only two of the 27 organizations on the fixed list did not participate in an interview. After multiple interview requests, senior officials at one private company and one academic PRO did not respond. To maintain confidentiality, these two organizations are unnamed in my work.

As with the preliminary round of expert interviews, the organizational key informant interviews were conducted using a touch screen computer running the network data collection platform EgoWeb 2.0 ("EgoWeb,"). Draft interview questions were reviewed by the five system-level experts and then revised to clarify language, expedite data entry, and better reflect the context of ocean science and technology. The same structured interview questions were used for all types of organizations—private companies, PROs, other public organizations, and not-for-profit organizations. Interviews ranged from approximately 30 to 90 minutes in length. Screenshots of the full interview instrument can be found in Appendix C.

To reduce interviewee burden, the interviews did not include superfluous questions (Borgatti et al., 2013). Respondents first signed the consent agreement and confirmed tombstone data, including their organization's official name, their email address, and whether or not they consented to being contacted with project updates or for future studies. The interview then consisted of seven components. First, respondents were asked simple questions about (1) the type of organization they were representing: academic, government research, other government, private company, not-for-profit; (2) the total number of full-time equivalent employees working at the organization, and the number working in research & development; (3) the kinds of outputs the organization produced over the previous five years and the novelty of those outputs; and (4) whether there had been any changes to the way these outputs were produced over the previous five years, and the novelty of those changes. The majority of time in each interview was devoted to the final three components, which elicited the network data.

The final three components took up the majority of the time allotted for each interview, and followed a standard "personal-network research design" (Borgatti et al., 2013). This personal-network research design produces ego-network data: data on the network of alters, or relations, around each ego, or focal organization. A standard personal-network interview instrument includes two phases of network questions: a name generator questions to establish a list of alters, followed by name interpreter questions to collect data about the alters and about ego's relationships with them. For this study, the name generator used a roster recall approach. The roster recall approach involves prompting interviewees with a pre-defined list of network participants. Roster recall is not only consistent with a fixed list approach, but it eliminates respondent recall error and limits the biases associated with the probability that one network actor will select another network actor (Borgatti et al., 2013; J. C. Johnson, Boster, & Palinkas, 2003). The alternative approach—free recall—would only be preferable if the research question required an unrestricted set of alters and if the research design used snowball selection (Borgatti et al., 2013).

Each respondent was presented with a roster that included the 27 organizations on the fixed list, plus the 20 additional organizations that were named by only two experts.

Respondents were asked to review the roster and identify those organizations on the roster that their organization usually interacted with over the past five years (part 5 of the interview).

Each interview concluded with name interpreter questions (parts 6 and 7 of the interview). The EgoWeb software (Kennedy & McCarty, 2016) and touch-screen computer interface facilitated a smooth name interpreter process. The name interpreter questions were presented as grids that contained all selected alters as rows and the response options as columns (see Figure 5). This multigrid format has an important psychological effect on respondents because it appears short, compact, and less burdensome than alternative presentations (Borgatti et al., 2013). Participants appeared comfortable with the touch screen interface: many collaborated with me to enter their responses into the system.

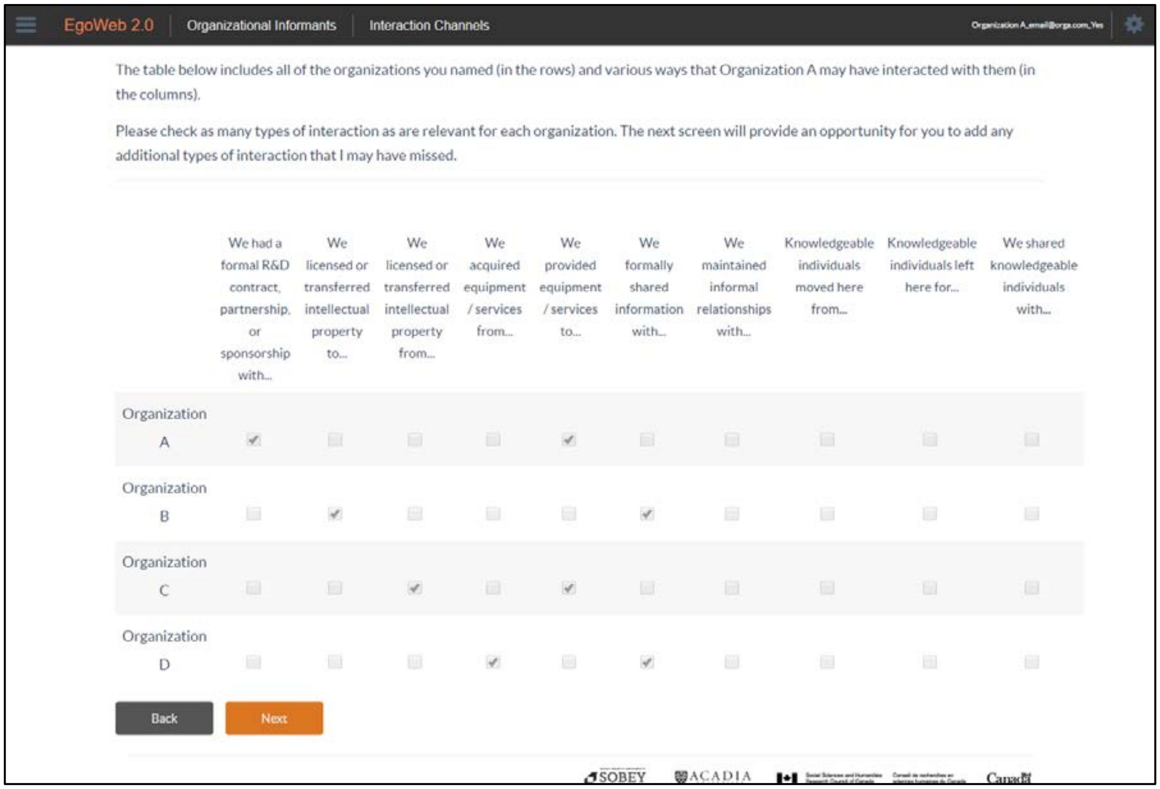

Figure 6. Screenshot of the multigrid interactive learning relationships component of the interview instrument, in EgoWeb 2.0 (2016).

For the second name interpreter question, the seven types of interactive learning relationships identified in Chapter 2, Table 2 were used. All relations that can have directionality were presented twice. For example, respondents could say that they licensed or transferred intellectual property *to* an alter organization, and/or that they licensed or transferred intellectual property *from* an alter organization. This meant that respondents could choose from among the

10 different interactions listed in Figure 5 above, and select all that applied. On the following screen, they were provided with an opportunity to identify other types of interactions that were not listed. Respondents typically wanted to use the “other” field to

provide additional description of relationships that were already captured under one of the 10 categories in Figure 5. However, two additional types of relations were captured multiple times in the “other” field: financial contributions and association memberships. In the first case, respondents noted loans, grants, and other financial support received from various public organizations. In the second case, they noted their membership status in the Ocean Technology Council of Nova Scotia and other not-for-profit associations. For each of these financial and membership relationships, probes were used to ensure that the appropriate interactive learning relationships had been selected on the previous screen. For example, if an association membership coincided with informal learning interactions then that relation was selected. In some cases, public financing and association memberships did not coincide with any interactive learning relations, so that pair of organizations was not considered to have a relationship in the interactive learning network (see discussion on the relationship boundary specification in Chapter 4).

Personal-network research designs sometimes include an optional third phase of name interrelator questions that collects data on the connections between alters. However, including this third phase of questions introduces considerable interviewee burden because it is time-intensive (Borgatti et al., 2013). Rather than using a name interrelator to collect nearly identical whole networks from each respondent, I used the common approach of aggregating ego-alter data across all respondents (Borgatti et al., 2013). This approach involved overlaying and merging network data from multiple respondents into one whole network that includes all respondents and the relations among them. A convenient by-product of this process is triangulation of the network data, which contributes to increased data reliability (Borgatti et al., 2013).

Data Management

Handling of missing data. This data fusion also provides an opportunity to reliably reconstruct minimal levels of missing data (Huisman, 2009; Stork & Richards, 1992). This reconstruction is possible because the responses provided by each respondent overlap with missing values from each non-respondent. Huisman (2009) demonstrated that reconstruction corrects for the effects of nonresponse in network data. As noted above, only two of the 27 organizations on the fixed list did not participate in an interview. However, all 25 participating organizations provided data on their relations, or lack of relations, with the non-respondent organizations. These two nodes can therefore be included in the network, as data was collected on 25 of their 26 possible relationships.

In compiling my data, I addressed three minor limitations of the missing data. First, the attributes of each organization—age, size, geographic location, and R&D intensity—had to be identified from publicly accessible secondary sources rather than self-reports. This data was publicly available for the nonresponding PRO. It was also publicly available for the nonresponding company, except for the proportion of FTEs that company devoted to R&D. The average R&D intensity for private companies (41%) was imputed for this company, but as I point out in the next chapter, the R&D intensity variable was dropped from my analysis because it was not a significant predictor. The missing value for R&D intensity was not consequential.

The second limitation was that the relationship between the two non-respondent organizations could not be reconstructed. I did not have data about interactive learning between the two nonresponding organizations. This meant that 2 of the 702 possible relations—0.003% of the observations—were missing from the network dataset. Many studies have examined the impact of missing observations for network analysis (Borgatti, Carley, & Krackhardt, 2006; Kossinets, 2006; Stork & Richards, 1992; Wang et al., 2012) and a variety of modelling techniques have been developed to address such missing observations (Huisman, 2009; Robins, Pattison, & Woolcock, 2004; Ward, Hoff, & Lofdahl, 2003; Žnidaršič, Ferligoj, & Doreian, 2012). Because only one dyadic relationship was missing from my data, I did not engage in computer-aided modelling of the missing data. Instead, I conducted all analyses twice: first with the relationship recorded as “0” and then with the relationship recorded as “1”. Because there was no significant difference in the results under these two scenarios, I report the more conservative assumption—the absence of an interactive learning relationship.

The third limitation was that the relationships between the responding and nonresponding organizations—7.1% of the 702 observations—could not be not triangulated; I do not know whether responses from the nonresponding organizations would have matched the responses from the responding organizations in the network. However, research on reliability issues in network data suggests that working with the non-triangulated data is acceptable (Stork & Richards, 1992). Stork and Richards (1992) explain that it is appropriate to reconstruct up to 40% of the data in a network, provided that nonrespondents are not systematically different from respondents and the confirmation rate between respondents is at least moderate. Both conditions are favourable in this study. The two nonresponding organizations each have 10-12 peer organizations in the network—other similar companies and PROs, all of which operate in the same region and the same socio-technical regime. Furthermore, the confirmation rate between respondents was high: in 86% of cases, both parties agreed on the presence or absence of an interactive learning relationship. Stork and Richards (1992) do not provide criteria for assessing the strength of confirmation rates, but Robins et al. (2004) argue that 38% is high. They then demonstrate a reconstruction approach for network data with a 90% confirmation rate (Robins et al., 2004). The reconstruction approach is therefore appropriate to these circumstances, and the result is a whole network dataset that is missing less than 1% of the possible observations.

Measures. Data was aggregated across interviews using the data manipulation functions in EgoWeb (Kennedy & McCarty, 2016), Microsoft Excel, and UCINET (Borgatti, Everett, & Freeman, 2002). Data was first exported from EgoWeb (Kennedy & McCarty, 2016) in an edge-list comma-separated values (.csv) format and then imported to Excel for deidentification and data cleaning. During this process, the names of individual key informants and the names of private companies were replaced with nondescript alpha-numeric codes. Attribute data for organizations in the network was moved into a separate .csv spreadsheet (i.e., the nodal attribute sheet). The edge-list and nodal attribute sheets were then imported into UCINet (Borgatti et al., 2002) and this final piece of software provided the functions necessary to convert the spreadsheet data into a series of adjacency matrices. A careful step-wise approach was used to avoid data manipulation errors (Borgatti et al., 2013). The resulting dataset consists of 16 variables that are constructed as adjacency matrices and 3 variables that capture node attributes in simple arrays. Because there are 27 nodes in the network, the adjacency matrices all consist of 702 dyadic observations, n=(n-1). The measures are described below.

(1) Master Relations Matrix. When any type of interactive learning relationship was reported between any two organizations in the network, this was entered as a value of “1”

in the appropriate cell of an undirected and symmetrical adjacency matrix called MASTER. When no relationships were reported between a pair of organizations, a value of “0” was entered in the corresponding cell in the matrix. Of the 351 dyads in this matrix, 225 pairs of organizations had engaged in some form of interactive learning over the previous five years and 125 pairs had not. A conservative approach was used for the one remaining relationship—the interaction between the two non-respondent organizations was imputed as “0” per the preceding discussion about the handling of missing data.

(2) Degree Centrality Array. Degree centrality scores were calculated for each organization based on the master relations matrix. Degree centrality is the row sum of the matrix (Borgatti et al., 2013). These scores were recorded in a nodal attribute array called DEGREE.

(3) Edge Betweenness Matrix. Edge betweenness scores were calculated for each edge in the master relations matrix. The value is a count of the number of times an edge lies on the shortest path between any two pairs of nodes (L. C. Freeman, 1977; Girvan & Newman, 2002). Where relations were not present in the master relations matrix, an edge betweenness score of “0” was recorded. Edge betweenness values were recorded in an undirected adjacency matrix called BETWEENNESS.

(4-10) Types of Relations Matrices. Separate matrices were also constructed to capture each of the seven types of interactive learning relationships. These seven matrices are described in Table 8. Three of these matrices are not symmetrical because they capture interactive learning relationships that are directed. The other four matrices capture bidirectional flows and are therefore mathematically symmetrical and undirected. All

seven matrices were combined into a multiple matrix dataset called RELATIONS using the matrix operation functions in UCInet (Hanneman & Riddle, 2005). Rather than simulate all possible observations for the missing pair of organizations, the two corresponding observations were coded as missing in the RELATIONS matrix.

Table 8

List of Adjacency Matrices that Correspond with the Seven Types of Interactive Learning Relationships

Interaction Channel	Relationship Option(s) Provided in the Interview	Matrix Variable Name	Type	True/False
R&D Projects and Consultancy	"We had a formal R&D contract, partnership, or sponsorship with..."	R&D	Undirected	218 / 482
Intellectual Property Rights	"We licensed or transferred intellectual property to…" and "We licensed or transferred intellectual property to from..."	IPflow	Directed	17 / 683
Human Resources	"Knowledgeable individuals moved here from…" and "Knowledgeable individuals left here for..."	HRflow	Directed	52 / 648
	"We shared knowledgeable individuals with..."	HRsharing	Undirected	100 / 600
Information & Training	"We formally shared information with..."	FormalInfo	Undirected	200 / 500
	"We maintained informal relationships with..."	InformalInfo	Undirected	332 / 368
Capital Equipment and Technical Services	"We acquired equipment / services from..." and "We provided equipment / services to..."	EquipServices	Directed	148 / 552

(11) Multiplex Relations Matrix. When any two or more types of interactive learning relationships were reported between any two organizations in the network, this was entered as a value of "1" in an undirected and symmetrical adjacency matrix called MULTIPLEX. When fewer than two types of interactive learning relationships were reported, a value of "0" was entered in the matrix. In other words, a multiplex tie was

observed if two organizations were connected in any two or more of the matrices listed in Table 8. Of the 350 dyads in this matrix, 152 pairs had engaged in multiplex interactive learning and 198 pairs had not. One pair was coded as missing.

(12) Bidirectional Relations Matrix. A bidirectional tie was observed for a pair of organizations if a relation was recorded in any of the bidirectional RELATIONS matrices: RandD, HRsharing, FormalInfo, or InformalInfo. A bidirectional tie was also observed when at least one in-flow and at least one out-flow were recorded in any of the directed RELATIONS matrices: IPflow, HRflow, or EquipServices. Based on these rules, an undirected and symmetrical adjacency matrix called BIDIRECTIONAL was constructed. Of the 350 dyads in this matrix, 112 pairs had engaged in bidirectional interactive learning and 238 pairs had not. One pair was coded as missing.

(13) Geographic Proximity Matrix. The latitude and longitude of each organization's place of business was determined by entering their civic address into the website http://www.latlong.net/. The spherical distance calculator in UCInet (Borgatti et al., 2002) was then used to produce a matrix of distances in kilometres between each pair of organizations. Eight pairs of participants were co-located at 0 km apart. The average distance between any two participants was 57.45 km (SD = 87.09 km), and the most distant pair was 410.63 km apart. Following Sorenson et al. (2006), distance values were rescaled using the formula, $x = -1[log(distance)]$.

(14) Organization Type Array. Each respondent identified their organization as one of five types (values in parentheses were recorded in the interview software): a private company (1), an academic organization (university or college) (2), a government research organization (3), a non-research government organization (4), or a not-for-profit

organization (5). This data was recoded to produce the variable ORGTYPE. Private companies retained the value of "1". Academic and government research organizations were recoded as PROs and assigned a value of "2". All other organizations were assigned a value of "3". This coding scheme worked for all organizations except the Advanced Diploma in Ocean Technology Program (ADOT) at NSCC. The ADOT was classified as an academic organization, but it does not perform research. It was therefore recoded as an "other" type of organization, i.e., not a PRO. The ORGTYPE variable was recorded as a nodal attribute array in UCInet.

(15) Public Research Organizations Array. Data on organizational types was further transformed to create a dummy-coded Boolean variable called PRO. In this nodal attribute array, all PROs were assigned a value of "1" and all other types of organization were assigned a value of "0". The The PRO variable was recorded as a nodal attribute array in UCInet.

(16) PRO-Industry Matrix. Based on ORGTYPE and PRO, a dummy-coded Boolean matrix variable was created with all possible relationships between PROs and companies coded as "1" and all other relations—e.g., PRO-PRO, Company-Company—coded as "0". This PRO-I variable was recorded as an adjacency matrix in UCInet.

(17) Organization Age Matrix. The year of incorporation, registration, or establishment for each organization was identified from public online sources. The age of each organization was then calculated by subtracting from the base year, 2017. Organizational ages were first recorded in a nodal attribute array, then an adjacency matrix called AGE was constructed using the attribute-to-matrix function in UCInet. For

each pair of organizations, the lowest of the two age values was used to represent the number of years in which an interactive learning relationship could have formed.

(18) Organization Size Matrix. Each respondent provided an estimate of the number of full-time equivalent (FTE) employees working for their organization in Nova Scotia. For the two non-respondent organizations, this data was available from public online sources. The number of FTEs was recorded in a nodal attribute array called SIZE. An adjacency matrix was then constructed using the attribute-to-matrix function in UCInet. Each cell in the matrix was calculated as the sum of the sizes for the two corresponding organizations. These values represent the number of FTEs potentially engaged in interactive learning across each edge.

(19) R&D Intensity Matrix. Each respondent also provided an estimate of the number of FTE employees who were devoted to research and/or development activities. The number of FTEs devoted to R&D was divided by the total number of FTEs in the organization to produce an R&D intensity score. This score was recorded in a nodal attribute array called INTENSITY. As noted above, this data was publicly available for one of the nonresponding organizations and the other organization was assigned the average intensity score for its peers in the networ—i.e., the other private companies (41%). An adjacency matrix was then constructed using the attribute-to-matrix function in UCInet. Each cell in the matrix was calculated as the sum of the intensity scores for the two corresponding organizations. This is a proxy for the total absorptive capacity across each edge.

Data quality. The internal validity of data was checked through respondent verification and data triangulation. After each interview, respondents received an email thank you message with an attached output of the data they provided. Respondents were asked to reply with any errors or omissions. Four respondents corrected minor errors in the validity of the data they had provided during their interviews. An additional six respondents verified that there were no errors in the data they provided. As discussed above, the data from each organization was also triangulated against data from other respondents. This triangulation was a by-product of aggregating the individual ego-networks into a whole network dataset. These verification and triangulation techniques helped to confirm the validity of the data (Bryman et al., 2011; Yin, 2009).

Even with respondent verification and data triangulation, the principle threat to validity of network data is nonresponse bias (Borgatti et al., 2013). I addressed the challenge of the two nonresponding organizations using the reconstruction approach, which is well-supported by the network analysis literature (Huisman, 2009; Stork & Richards, 1992). As discussed above, I also took several steps to minimize interviewee burden because it is the principle cause of nonresponse during network interviews (Borgatti et al., 2013). I chose a face-to-face interview format to increase rapport, used a roster-based name generator and multigrid name interpreter to expedite interviewee responses, and did not include superfluous questions in the interview instrument. These steps are consistent with the recommendations provided by Borgatti et al. (2013) for managing nonresponse within network interviews. In this way, threats to validity were addressed by following best practices for network data collection (Borgatti et al., 2013).

One further threat to data quality relates to internal reliability. Network data collection is particularly susceptible to interviewer effects, which are variations in the ways that multiple interviews are delivered and perceived (Carrington, Scott, &

Wasserman, 2005). These interviewer effects are most evident in the name generator phase of network interviews due to inconsistent elicitation of alters. This problem was avoided through the use of a fixed-list roster recall name generator (Borgatti et al., 2013). Carrington et al. (2005) argue that standardized administration of interview questions also addresses this issue. To this end, all interviews were conducted by the same interviewer. The interviews were also structured to ensure consistency, and the interview questions were visible to the interviewees on the data collection computer throughout each interview. Follow-up prompts—sometimes called elicitation probes (Brewer, 2000)—were also provided on-screen and used in all interviews to ensure reliability.

The total data collection effort entailed 35 first-person interviews, averaging 1 hour in length. Expert interviews were conducted in July 2016 and organizational key informants were interviewed between August 2016 and February 2017. In this chapter I have described the careful approach that was taken over this period to ensure a high-quality network dataset. The most important implication of the data collection process is public and private organizations were treated equally. A roster of organizations was identified by system-level experts and this roster included any type of organization that fell within the network boundary specification criteria. Then, key informants with those organizations all responded to the same structured interview, regardless of public/private sector distinctions. Because all organizations were treated equally for data collection, it is now possible to test the four hypotheses developed in Chapter 4 and to then draw conclusions regarding the importance of public organizations for ocean science instrumentality innovation in Nova Scotia.

Chapter 6: Analysis & Results

This chapter presents an analysis of the interactive learning network for ocean science instrumentalities in Nova Scotia. First, I describe the network in general terms. Then, I provide descriptive statistics regarding the types of product and process innovations that were found within the network and the novelty of these innovations. I then present results from each hypothesis test: first, the hypothesis regarding network position (H1), then the hypotheses regarding network composition (H2 and H3), and finally the hypothesis regarding network dynamics (H4). I conclude the chapter by summarizing these results and laying the foundation for discussion and conclusions in Chapter 7.

Descriptive Statistics

The network. The interactive learning network is one strongly-connected component that comprises 27 organizations (see Figure 6). In other words, no organizations were isolated and all organizations were reachable through paths of interorganizational interactive learning relationships. The network includes 12 scientific instrumentality companies and 10 PROs. The 10 PROs are listed and described in Table 9. The network also includes five organizations that are highly engaged in ocean science, but do not directly engage in scientific investigations. One of these is a teaching unit of the Nova Scotia Community College. Four of these are not-for-profit organizations that meet two of the three criteria developed by Perry and Rainey (1988) for being classified as public organizations. I have therefore labelled all five of these organizations as public support organizations. They are listed and described in Table 10. All told, the 27 organizations in this network have an average degree of 16.67. The average distance between any two nodes is 1.36 edges. The network density is 0.64, indicating that 64% of the possible dyadic relationships are present.

Types of innovation. Table 11 provides a summary of the product and process innovations reported by participating organizations. All participating organizations were involved in the production of novel outputs (i.e., outputs that were new to the world or new to their field, sector, or market) and had incorporated some process innovations over the past 5 years. Indeed, R&D intensity—a proxy for absorptive capacity—was high throughout the network: 44% of the 1,783 employees were dedicated to research and/or development activities. The average R&D intensity of public support organizations was lower (16%) than the R&D intensity of PROs (46%) and companies (41%).

I asked respondents to indicate the types of outputs produced by their organization over the past five years. All five product types were reported by a majority of respondents. This included “instruments, machinery, and equipment” which were produced by 20 of the 25 responding organizations. It is interesting that all the companies, eight of the PROs, and one of the public support organizations engaged in the production of instruments, machinery or equipment. Novelty levels were also high across all three types of organizations. All the PROs, nine of the companies, and three of the public support organizations reported introducing goods or services that were “new to the world” over the past 5 years.

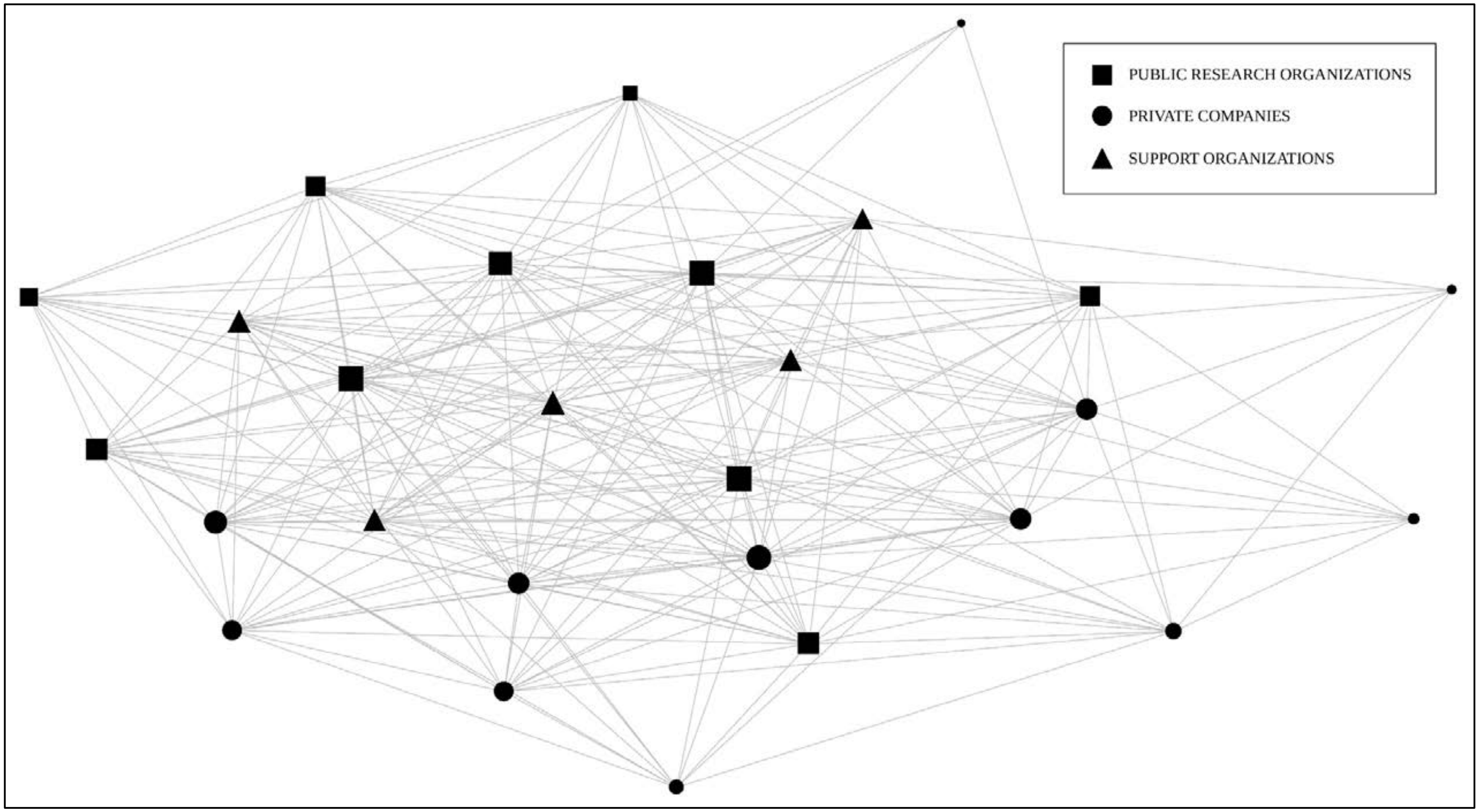

Figure 7. Interactive learning network for ocean science instrumentalities in Nova Scotia, Canada. Graph produced in NetDraw (Borgatti, 2002) with nodes sized by degree.

Table 9

Public Research Organizations in the Interactive Learning Network

Organization	FTEs	R&D Intensity	Degree Centrality	${}^{D}F$
Acadia Tidal Energy Institute	11	98%	14	-0.004
Bedford Institute of Oceanography (Department of Fisheries and Oceans)	700	21%	22	0.008
Bedford Institute of Oceanography (Natural Resources Canada)	55	82%	17	0.001
Verschuren Institute, Cape Breton University	40	90%	16	-0.001
Oceanography Department, Dalhousie University	118	97%	22	0.008
Defense Research and Development Canada: Atlantic Research Centre	165	61%	22	0.008
Applied Geomatics Research Group, Nova Scotia Community College	20	75%	12	-0.007
Applied Oceans Research Group, Nova Scotia Community College	10	100%	21	0.007
Ocean Tracking Network, Dalhousie University	12	88%	18	0.002
Academic Kind-of-Activity Unit (non-participant)	—	—	18	0.002

Note. ${}^{D}F$ = distance-weighted fragmentation (Borgatti, 2006); FTEs = full-time equivalent employees. All organizations in this table are public, per the criteria developed by Perry and Rainey (1988): they are all under public ownership, receive public funding, and operate under polyarchal social control. Size and R&D intensity for the non-participating PRO were available from online sources, but are supressed in this table to maintain confidentiality.

Table 10

Public Support Organizations in the Interactive Learning Network

Name	Ownership	Funding	Control	FTEs	R&D Intensity	Degree Centrality	^{D}F
Fundy Ocean Research Centre for Energy	Private[1]	Public	Polyarchy	10	40%	19	0.004
Institute for Ocean Research Enterprise	Private[1]	Public	Polyarchy	4	13%	19	0.004
Advanced Diploma in Oceans Technology Program, Nova Scotia Community College	Public	Public	Polyarchy	2	0%	19	0.004
Marine Environmental Observation Prediction and Response	Private[1]	Public	Polyarchy	7	0%	17	0.001
Offshore Energy Research Association of Nova Scotia	Private[1]	Public	Polyarchy	5	0%	21	0.007

Note. ^{D}F = distance-weighted fragmentation (Borgatti, 2006); FTEs = full-time equivalent employees.

[1]These organizations are legally constituted as not-for-profit corporations and therefore classified as “privately held.” However, they are all considered public organizations under the criteria developed by Perry and Rainey (1988) because they receive public funding and they operate under polyarchal control rather than under market forces.

All responding organizations incorporated some degree of process innovation into their operations over the past 5 years. Nearly all organizations introduced new production techniques/methods and adopted new software. A sizeable majority (84%) also reported introducing new machinery or equipment into their operations. There were fewer organizations involved in novel process innovations than in novel product innovations. Nonetheless, 56% of organizations reported process innovations that were “new to the world”.

The types of innovation and innovation novelty levels reported here confirm the high levels of innovation activity in this relatively small interactive learning network. It is particularly important to note that public research organizations and public support organizations in this network all reported high levels of R&D intensity, product innovation, and process innovation. Most interestingly, innovative goods—instruments, machinery or equipment—were produced by 9 of the 14 public organizations in this study. Note that this finding alone runs counter to the widespread assumption—discussed in Chapter 1—that innovation in goods is the exclusive domain of the private sector. These results are therefore revelatory in that they confirm the production of innovative technological goods by public organizations.

Table 11

Product and Process Innovations in Nova Scotia's Ocean Science Instrumentalities Innovation System

	PROs	Companies	Support Orgs	Total
Number of Organizations	10	12	5	25
Employees (full-time equivalents)	1,281	474	28	1,783
R&D Intensity[1]	46%	41%	16%	44%
Product Innovations[2]				
Percent of organizations that produced…				
instruments, machinery or equipment	89%	100%	20%	80%
reports, information, documents or manuscripts	100%	45%	80%	72%
computer software or datasets	78%	73%	60%	72%
education, training or professional development	89%	73%	100%	84%
data collection, processing or analysis services	100%	45%	60%	68%
Percent of organizations introducing products that were…				
new to the organization	78%	73%	100%	80%
new to the field, sector or market	89%	73%	60%	76%
new to the world	100%	82%	60%	84%
Process Innovations[2]				
Percent of organizations that introduced new…				
techniques or methods	100%	100%	80%	96%
machinery or equipment	100%	73%	80%	84%
software	100%	91%	80%	92%
Percent of organizations introducing processes that were…				
new to the organization	89%	82%	60%	80%
new to the field, sector or market	89%	64%	60%	72%
new to the world	100%	36%	20%	56%

Notes. [1]R&D Intensity is the proportion of total employees (full-time equivalents) devoted to research and/or development. [2]Percentages based on 25 organizations, which excludes one non-responding PRO and one non-responding company.

Centrality (H1)

As noted in Chapter 2, prior research demonstrated that scientists, rather than private companies, are the locus of innovation for scientific instruments (Riggs & von Hippel, 1994; Spital, 1979; von Hippel, 1976, 1988). I therefore proposed that PROs—organizations that employ scientists and use scientific instrumentalities—will be the locus of innovation for a scientific instrumentalities innovation system. In Chapter 4, I noted that the loci of an interactive learning network are those organizations with the greatest degree centrality. My hypothesis (H1) was: PROs have significantly greater average degree centrality than all other types of organizations in a scientific instrumentalities interactive learning network.

I conducted a quadratic assignment procedure (QAP) *t*-test to compare the degree centrality of public research organizations with the degree centrality of other organizations in the network: private companies and public support organizations. The degree centrality scores for PROs (M=18.20, SD=3.37) were not significantly higher than the degree centrality scores for other organizations in the network (M=15.65, SD=5.34); $t(25) = 2.55$, $p = 0.11$. Hypothesis 1(a) was not supported. This result suggests that the slightly higher average degree centrality for PROs in this network could occur at random: a similar difference in means occurred in 11% of 10,000 random permutations of the observed data.

In interpreting this result it is important to note that H1 was drawn from a literature on scientific instrumentality innovation that does not discuss public support organizations (i.e., de Solla Price, 1984; Gorm Hansen, 2011; Kline, 1985; Kline & Rosenberg, 1986; Riggs & von Hippel, 1994; Rosenberg, 1992; Spital, 1979; von Hippel, 1976, 1988). Prior studies of scientific instrument innovation examined the relative importance of only two roles: "users" and "producers" (Riggs & von Hippel, 1994; Spital, 1979; von Hippel, 1976, 1988). These studies did not include any individuals or organizations that were similar to the public support organizations in Nova Scotia's ocean science instrumentality innovation system. It is possible that similar public support organizations did not exist at the time or in the context of prior research. Indeed, such organizations did not appear in the historical data for Nova Scotia's ocean science instrumentalities innovation system (see Chapter 3). They are likely a relatively recent addition (see further discussion in Chapter 7).

To further understand the impact of public support organizations on my results for H1, I conducted a post hoc hypothesis test (H1b). If this study had used a data sampling approach, post hoc hypothesis testing using classical statistical tests would be problematic; there would be a high risk of type 1 error. However, there are fundamental differences between the assumptions underlying classical statistical tests of sample data and the assumptions underlying QAP hypothesis tests of whole network data (Borgatti et al., 2013; Dekker, Krackhardt, & Snijders, 2007; Krackhardt, 1988). It is appropriate to state and test post hoc hypotheses in this study because the dataset includes the whole network population—not a sample, and because the significance of each result is evaluated using a new, randomly-generated distribution of permuted observations—not an assumed normal distribution. Under these network analysis conditions, it is normal and appropriate to conduct post hoc tests (e.g., Grosser, Lopez-Kidwell, & Labianca, 2010; Kilduff, 1992; Lopez-Kidwell, 2013; Soltis, 2012; Tang, Wang, & Kishore, 2014) and to undertake exploratory data analysis (e.g., Borgatti et al., 2013; Butts, 2008; De Nooy, Mrvar, & Batagelj, 2011).

My post hoc hypothesis test (H1b) was that public organizations have significantly greater average degree centrality than private companies in this network. I conducted a QAP *t*-test to compare the mean degree centrality of public organizations—PROs and support organizations—with the mean degree centrality of private companies. I found that the degree centrality scores for public organizations (M=18.47, SD=2.87) were significantly higher than the degree centrality scores for private companies (M=14.25, SD= 5.75) in this network; $t(25) = 4.22$, $p = 0.02$. The post hoc hypothesis (H1b) was supported. This could suggest that public organizations—PROs and support organizations—are more important than private companies in the interactive learning network. The relatively lower degree centrality scores for private companies in this network is consistent with prior conclusions that private manufacturers are less important—i.e., not the "locus"—for scientific instrument innovation (Riggs & von Hippel, 1994; Spital, 1979; von Hippel, 1976, 1988). The highest degree scores in this network are found among a combination of public organizations, including both PROs and public support organizations. This may suggest that public support organizations are an important extension of the scientific enterprise, even if their employees do not directly perform scientific investigations.

Because degree centrality is a common proxy for importance in a network (Borgatti et al., 2013; Gay & Dousset, 2005; Takeda et al., 2008), the foregoing is a common interpretation of differences in degree centrality. However, there is an alternative explanation that cannot be discounted: higher degree centrality scores could also suggest that public organizations in this system have a greater propensity to establish interactive learning relationships than private companies in this system. For now, a cautious interpretation of the results for H1(b) is that public organizations are more connected within this network than private companies. The relative importance of different organizations will be revisited in the results for H4.

Symbiosis (H2)

The literature on scientific instrumentality innovation discusses symbiotic relationships between those who produce science and those who produce scientific instrumentalities (de Solla Price, 1984; Gorm Hansen, 2011; Rosenberg, 1992). I have therefore proposed that the majority of relationships between PROs and instrumentality companies include multiple concurrent types of interactive learning with knowledge flows in both directions. In network terms, such relations should be multiplex and bidirectional. My hypothesis (H2) was: within a scientific instrumentalities interactive learning network, relations between PROs and private companies are multiplex and bidirectional.

Out of the 702 possible relations in this network, there are 240 possible relations between PROs and instrumentality companies. Interactions were reported for 124 of these dyadic pairs. Seventy-four of these interactions were multiplex. Ninety-two relations were bidirectional. Seventy relations were both multiplex and bidirectional.

I calculated a Jaccard similarity coefficient to assess the degree to which the set of relationships between PROs and instrumentality companies (MASTER-PRO-I) intersected with the set of multiplex and bidirectional PRO-company relations (SYMBIOTIC-PRO-I). For this test, the Jaccard coefficient was more appropriate than a

Pearson correlation coefficient because the data are binary (Hanneman & Riddle, 2005). The Jaccard coefficient is an index of the similarity between two sets of binary values. The hypothesis was focused on the composition of PRO-company relations, so the test was conducted using only the data on PRO-company dyads. In other words, support organizations were not included in this analysis, nor were PRO-PRO and Company-Company relations. The results of the test were assessed for significance using the QAP with 10,000 permutations[25]. I found a significant similarity between the two sets of relations, $J = 0.56$, $n = 124$, $p < 0.001$. The majority (56%) of observed relationships between PROs and instrumentality companies were multiplex and bidirectional. Hypothesis 2 was supported.

Channels of Interaction (H3)

In Chapter 2, I developed a channels of interactive learning model and proposed that the capital equipment and technical services channel is important for scientific instrumentality innovation. Then, in Chapter 4, I presented the concept of edge betweenness as a measure of the importance of ties in a network. My hypothesis (H3) was: the presence of a capital equipment and technical services interaction significantly and positively predicts the edge betweenness of a relationship in a scientific instrumentalities interactive learning network.

I used the double Dekker semi-partialling (DSP) multiple regression technique (Dekker et al., 2007) to assess the effects of my channels of the interactive learning model

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[25] The distribution of similarities for the 10,000 random permutations ranged from 4% to 54% ($M = 23.2\%$, $SD = 6.3\%$).

on edge betweenness. Dekker et al. (2007) demonstrated that the DSP technique is the most appropriate choice for fitting linear models, such as this, that include continuous and network count data. The dependent variable, edge betweenness, was produced from the master relations matrix. Independent variables included the seven types of interactive learning relations: R&D Partnerships, IP flows, HR flows, HR sharing, formal knowledge sharing, informal knowledge sharing, and the provision/acquisition of capital equipment or technical services. Additional variables were included to control for geographic proximity, the potential age of a relationship, the size of organizations, and R&D intensity. One model also controlled for PRO-Industry relations, a theoretically-important category of relationships in the network. Further to the results presented earlier, also I tested a second model that replaced the PRO-I control with a control for relations between public and private sectors (Public-Private). Descriptive statistics and intercorrelations for all variables can be found in Table 12. Note that collinearity of independent variables was not an issue, $r_{i,j} < 0.70$ (Meyers, Gamst, & Guarino, 2013). Skewness was also not an issue because the DSP technique is robust for skewed data under situations where spuriousness is not high. The various control variables listed above are those identified in the literature (see Chapter 4) and were included to ensure low levels of spuriousness.

All four iterations of the model significantly predicted edge betweenness, $n = 700$, $p < .001$, adj. $R^2 = .36$. Note that the DSP regression technique does not incorporate an F-statistic like ordinary linear regression: the significance of the R^2 fit statistic is evaluated by comparison against the distribution of R^2 values for 10,000 random permutations. Regression coefficients and standard errors for the DSP multiple regression models can be found in Table 13.

Table 12

Intercorrelations and Descriptive Statistics for Variables in the Multiple Regression Models

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. Edge Betweenness														
2. Informal	0.51**													
3. Formal	0.35**	0.50**												
4. HR Flows	0.18**	0.09*	0.09*											
5. HR Sharing	0.19**	0.33**	0.30**	0.20**										
6. IP Flows	0.07	0.11**	0.21**	0.10*	0.07									
7. R&D	0.39**	0.40**	0.46**	0.20**	0.61**	0.17**								
8. Equip. & Services	0.34**	0.25**	0.30**	0.11*	0.22**	0.19**	0.31**							
9. Proximity	0.13**	0.15	-0.01	0.11*	0.13*	0.00	0.01	0.13*						
10. PRO-I	-0.09	-0.27**	-0.15*	-0.05	-0.14*	-0.02	-0.17**	0.03	-0.03					
11. Public-Private	-0.15**	-0.28**	-0.23**	-0.07	-0.21**	-0.05	-0.18**	-0.05	0.01	0.70**				
12. Age	0.07	-0.03	0.00	0.23**	0.09	0.05	0.05	0.24**	0.23	0.18*	-0.01			
13. Size	0.15*	0.10	0.11	0.15*	0.09	-0.03	0.12	0.13*	0.18	0.14**	-0.03	0.42**		
14. R&D Intensity	-0.03	-0.12	0.04	-0.02	-0.09	0.05	-0.07	0.01	-0.21	0.37**	-0.01	0.04	-0.15	
Mean	1.36	0.47	0.29	0.07	0.14	0.02	0.31	0.21	-2.83	0.34	0.51	10.65	132.09	1.08
Standard Deviation	1.25	0.50	0.45	0.26	0.35	0.15	0.46	0.41	1.68	0.47	0.50	10.45	184.85	0.43
Minimum Value	0	0	0	0	0	0	0	0	0	0	0	3	5	0
Maximum Value	6.90	1	1	1	1	1	1	1	1	1	1	58	865	2

Note. Each variable is a 27 row by 27 column adjacency matrix. Listwise $N = 700$ (i.e., 2 missing observations). $^{*}p < .05$ and $^{**}p < .01$. Remaining correlations are *ns*. Correlations are based on 5,000 random permutations.

Table 13

Multiple Regression Models to Predict Edge Betweenness in the Interactive Learning Network

	Control 1 (R^2=.35, *p*<.001)			*Control 2* (R^2=.35, *p*<.001)			*Parsimony 1* (R^2=.35, *p*<.001)			*Parsimony 2* (R^2=.35, *p*<.001)		
	B		SE_B	*B*		SE_B	*B*		SE_B	*B*		SE_B
Independent Variables												
Informal Sharing	1.01	***	(0.13)	0.99	***	(0.13)	1.01	***	(0.13)	1.04	***	(0.12)
Formal Sharing	0.10		(0.13)	0.09		(0.13)	0.10		(0.13)			
HR Flows	0.50	**	(0.17)	0.48	**	(0.17)	0.53	**	(0.17)	0.53	**	(0.17)
HR Sharing	-0.54	***	(0.17)	-0.55	***	(0.17)	-0.53	***	(0.17)	-0.53	***	(0.17)
IP Flows	-0.45	*	(0.27)	-0.44	*	(0.27)	-0.47	*	(0.28)	-0.44	*	(0.27)
R&D Partnership	0.65	***	(0.14)	0.64	***	(0.14)	0.62	***	(0.14)	0.65	***	(0.14)
Equip. & Services	0.53	***	(0.12)	0.54	***	(0.12)	0.57	***	(0.12)	0.58	***	(0.12)
Control Variables												
Proximity	0.04		(0.04)	0.05		(0.04)						
PRO-Company	0.09		(0.11)									
Public-Private				-0.00		(0.09)						
Age	-0.00		(0.01)	-0.00		(0.01)						
Size	0.00		(0.00)	0.00		(0.00)						
R&D Intensity	0.09		(0.17)	0.13		(0.17)						
Constant	0.57			0.57			0.60			0.60		

Note. For all models, *N* = 700. $^{*}p < .05$, $^{**}p < .01$, and $^{***}p<.001$. Remaining coefficients are *ns*.

Note that none of the control variables added significantly to the models. This did not change when I replaced the PRO-I relations control variable ($B = 0.09$, $p = 0.18$) with a control for public-private relations ($B = -0.00$, $p = 0.49$). Given this result, I reduced the model to eliminate the superfluous control variables. The change in R^2 after removing the control variables was less than 0.01.

In the model without controls (labelled "Parsimony 1" in Table 13), the presence of a formal knowledge sharing relationship did not add significantly to the prediction of edge betweenness ($B = 0.10$, $p = 0.22$). A similar result can be observed for both control models. All other independent variables added significantly to the prediction of edge betweenness, $p < .05$. The sharing of human resources ($B = -0.53$, $p < 0.001$) and the licensing / transfer of intellectual property ($B = -0.47$, $p = 0.02$) were both significant negative predictors of edge betweenness. In other words, learning relationships were less important to the overall network if they included the licensing/transfer of intellectual property or the sharing of human resources—such as cross-appointments, sabbatical projects, or students on work placement in private companies. All other variables were positive predictors of edge betweenness, including the key channel under hypothesis 3: the provision / acquisition of capital equipment or technical services ($B = 0.57$, $p < 0.001$). Hypothesis 3 was supported. Note, however, that the size of the effect for this channel was less than the effect sizes for informal knowledge sharing ($B = 1.01$, $p < 0.001$) and R&D partnerships ($B = 0.62$, $p < 0.001$). In other words, the best predictor of the most important learning relationships in the network was informal knowledge sharing, followed by R&D partnerships, followed by the provision / acquisition of capital equipment or technical services.

In a final iteration of the model (labelled “Parsimony 2” in Table 13), I removed the formal knowledge sharing variable. This resulted in an R^2 change of less than 0.01; I achieved parsimony without compromising explanatory power. The removal of this variable resulted in increased effect sizes for informal knowledge sharing (B = 1.04, p < .001), IP flows (B = -0.44, p = 0.03), R&D partnerships (B = 0.65, p < .001), and the provision/acquisition of capital equipment and technical services (B = 0.58, p < .001). This suggests that formal knowledge sharing—such as shared training, workshops, or research coauthorship—did not directly contribute to the importance of interactive learning relationships in this network, but it did co-occur with other types of learning interactions that were significantly related to edge betweenness.

As predicted in my theoretical framework, all specifications of the model indicated that the use of a capital equipment and technical services channel was positively and significantly related to the importance of an interactive learning relationship in this network. However, informal knowledge-sharing relationships and formal R&D partnerships were stronger predictors of the most important relationships in the network. By demonstrating the relative importance of these channels in this context, my results extend prior discussion about the nature of interactive learning in scientific instrumentalities (de Solla Price, 1984; Gorm Hansen, 2011; Rosenberg, 1992).

Fragmentation (H4)

In Chapter 3, I presented historical evidence that suggesting that PROs may have served as anchor tenants in the evolution of this innovation system. Based upon my analysis of the historic context and on the theoretical framework I developed in Chapter 2, I proposed that a scientific instrumentalities innovation system will be more susceptive to the loss of PROs than to the loss of private companies. Then, in my analytical framework I introduced distance-weighted fragmentation (^{D}F) as a measure of changes in network cohesion. My hypothesis (H4) was: removing individual PROs from a scientific instrumentalities interactive learning network results in significantly greater distance-weighted fragmentation than removing other types of organizations.

I conducted a QAP *t*-test to compare the mean change in ^{D}F after removal of a PRO with the mean change in ^{D}F after removal of other organizations in the network (i.e., private companies and support organizations). The fragmentation scores for PROs (M=0.002, SD=0.005) were not significantly greater than the fragmentation scores for other organizations in the network (M=-0.001, SD=0.008); $t(25) = 0.004$, $p = 0.11$. Hypothesis 4(a) was not supported. This result suggests that the larger average fragmentation scores that were observed for PROs in this network could occur at random: differences that were the same or greater than the observed difference occurred in 11% of 10,000 random permutations of the observed data.

The result for this test is similar to the result for the test of degree centrality scores (H1). As with hypothesis 1, I formed a post hoc hypothesis to account for the presence of public support organizations in the data: removing individual public organizations from a scientific instrumentalities interactive learning network results in significantly greater distance-weighted fragmentation than removing private companies (H4b).

I conducted a second QAP *t*-test to compare the mean fragmentation scores for public organizations (i.e., PROs and public support organizations) with those for private companies. The fragmentation scores for public organizations (M=0.003, SD=0.004) were significant greater than the fragmentation scores for private companies (M=-0.004, *SD*=0.009); $t(25) = 0.006$, $p = 0.013$. The post hoc hypothesis (H4b) was supported. This result suggests that, on average, this innovation system would become more fragmented following the loss of a public organization than it would become following the loss of a private company. The results of this test are consistent with the results for hypothesis 1a/b: public support organizations appear to be an important extension of the scientific enterprise. This is not discussed in the existing literature on scientific instrument innovation, so it warrants further discussion in my final chapter.

Summary of Results

In this chapter I presented the results from various analyses of the interactive learning network for ocean science instrumentalities in Nova Scotia. The network includes 27 PROs, companies, and public support organizations. Key informants from all three types of organizations reported product and process innovations over the past 5 years. Further to prior research on scientific instrumentality innovation, but contrary to both neoliberal discourse and existing taxonomies of public innovation, the network included 9 public organizations that produced new goods.

The literature on scientific instrument innovation suggested that organizations employing scientists—PROs—would be more important/central in a scientific instrumentalities innovation network. In my results, public organizations involved in science did have greater centrality than private companies. However, the present-day scientific enterprise appears to include both PROs and public support organizations that do not directly engage in producing science. The full set of public organizations not only had greater average centrality than private companies, but was also more important to the cohesion of the network—the removal of a public organization from this network would result in greater average fragmentation than the removal of a private company.

In Chapter 2 I also proposed that certain types of interactive learning are particularly important for scientific instrumentality innovation. Further to hypothesis 2, I found that the majority of relations between PROs and instrumentalities companies in this network were multiplex and bidirectional. This is consistent with existing descriptions of symbiotic relationships in scientific instrumentality innovation (de Solla Price, 1984; Gorm Hansen, 2011; Rosenberg, 1992). However, the literature suggested that the provision/acquisition of capital equipment and technical services was the most important form of interactive learning. The presence of such equipment/service interactions did help predict the most important learning relationships in this network. Yet several other channels of interactive learning—informal knowledge sharing, R&D partnerships, and the movement of knowledgeable individuals—also predicted the most important ties in the network. The channel discussed in the literature was not the strongest predictor, and so my results provide an opportunity to extend the literature on scientific instrumentality innovation.

Taken together, the results of this network analysis are revelatory. This innovation system includes public organizations that are producing new to the world innovations, including new to the world scientific instruments, machinery and equipment. My analysis therefore shows that discussions of the entrepreneurial state and of public innovation can be expanded to recognize that public organizations produce novel goods. Note, however, that the important public organizations in this network were not only those that use scientific instruments to perform scientific investigations, as was suggested by the literature (Riggs & von Hippel, 1994; Spital, 1979; von Hippel, 1976, 1988). Several public support organizations were important to the scientific enterprise, suggesting the need to update our understanding of scientific instrumentality innovation. My investigations of the interactive learning channels/relationships in this network also contribute to a richer understanding of scientific instrumentality innovation. The next and final chapter discusses these insights and the contributions that arise from this work.

Chapter 7: Discussion and Contributions

In this dissertation I have asked, “how important are public organizations for scientific instrumentality innovation?” This question was a preliminary response to what I have called the public innovation in goods gap. I described the gap as a type of dark innovation: the role of public organizations in the development of technological goods is frequently acknowledged (e.g., De Vries et al., 2016; Fagerberg et al., 2013; Holbrook, 2010; Koch & Hauknes, 2005; Mazzucato, 2013a; Mazzucato & Penna, 2016; Windrum & Koch, 2008), but there is a lack of empirical research on public innovation in goods (Arundel & Huber, 2013). Most empirical research in this field is focused on innovation in public services and in public policy (e.g., Gallouj et al., 2013; Halvorsen et al., 2005; Koch & Hauknes, 2005; Mazzucato, 2013a, 2016; Windrum & Koch, 2008). The importance of public organizations for innovation is therefore underestimated. My study of Nova Scotia’s ocean science instrumentalities innovation system is a first attempt to address this gap. Thanks to a carefully developed theoretical framework, analytical framework, and research method, I conducted a network analysis that explored the importance of public organizations for innovation in ocean science instruments and techniques. In so doing, I have made some contributions toward two of Ben Martin’s (2013, 2016) grand challenges in innovations studies: the entrepreneurial state challenge and the dark innovation challenge.

In this final chapter, I discuss my findings and their implications. I begin by revisiting the first research objective I stated in Chapter 1: confirming that public organizations produce technological goods. To this end, I discuss the implications of my finding that several public organizations produced novel technological goods in this innovation system over the past 5 years. This finding points to an opportunity for expanded research on the entrepreneurial state, and it reinforces the call for innovation in goods to be included in studies of public innovation (Arundel & Huber, 2013). After discussing this finding, I turn to a discussion of the methodological contributions that made it possible. Martin (2013, 2016) asserts that new and revised research methods are necessary for uncovering dark innovation. After discussing some methodological contributions, I look more closely at the findings they accorded. I discuss the relative importance of public and private organizations for scientific instrumentality innovation (i.e., research objective 2) and then the nature of interactive learning relationships for scientific instrumentality innovation—particularly the relationships between public and private organizations (i.e., research objective 3). I revisit the metaphors of anchors and quartermasters introduced in Chapter 3 and use these to describe three roles that appear in this system. Because my focus is on ocean science instrumentalities and the province of Nova Scotia, Canada, my findings relate specifically to this context and may or may not transfer to other contexts. At the close of the chapter, I present the corresponding local policy implications and conclude by discussing limitations of my research and several future research directions.

Discussion

The entrepreneurial state challenge: Public innovation in goods. At the beginning of this work, I discussed the neoliberal belief that private companies operating in a free market are more effective innovation actors than public organizations which are seen to be outside the market. I joined a conversation that is underway about the influence of neoliberal ideas in innovation studies (see Archibugi & Filippetti, 2017; Cooke, 2016;

Cruz et al., 2015; Fløysand & Jakobsen, 2011; Gallouj & Zanfei, 2013; Lundvall, 2016). I highlighted the corresponding view—that public innovation should be focused on the efficient delivery of public services with minimal strain on the market. This perspective on public innovation restricts our understanding of the roles performed by public organizations; public innovation in goods is seen as anecdotally interesting, but it is a deviation from norms. Goods are typically missing from most research instruments that are used to measure public innovation (Arundel & Huber, 2013) and goods have been heretofore missing from most taxonomies of public innovation (Halvorsen et al., 2005; Koch & Hauknes, 2005). My research presents another perspective. I have carefully aligned theory, context, analytical approach, and methodological techniques so that I might investigate this aspect of innovation that is otherwise missing from the entrepreneurial state and public innovation research agendas.

My results suggest that some public organizations do produce innovation in goods. I found that technological goods—instruments, machinery, and equipment—were developed by 8 out of 14 public organizations in this innovation system over the past 5 years. Because this phenomenon is so rarely studied, my results would be interesting even if I had only observed one technological good produced by one public organization. By empirically observing this phenomenon in any quantity, I can assert that public innovation in goods exists and can be studied. As Barbara Spellman (2012) explains, “science proceeds not only by the accretion of new facts but also by the weeding out of what was once falsely believed” (p. 59). My results suggest it is false to believe that “technological innovations, especially goods, are the exclusive domain of the private sector” (Windrum & Koch, 2008, p. 239). This is the first contribution of my dissertation.

I have shown that public innovation in goods does occur and that neglecting goods and privileging service and policy innovation does not fully explain the roles of public organizations—or the entrepreneurial state—in innovation systems. Public organizations have been producing novel technological goods within Nova Scotia's ocean science instrumentalities innovation system. This finding reinforces calls by Arundel and Huber (2013) and Gault (2018) for goods to be included in the public innovation literature.

Apart from neoliberal hegemony, some readers may wonder whether there are other explanations for the limited research on public innovation in goods. One alternative explanation is that the goods produced by public organizations might be developed in-secret for the purposes of national defense, security, and intelligence. These would be the kinds of technological goods—such as the global positioning system (GPS)—that originate within the defense-security establishment and are not publicly revealed for long periods of time. However, this is a weak explanation for the absence of empirical research on public innovation in goods. These kinds of technologies do not remain secret; indeed, I argued in Chapter 1 that they are regularly included as anecdotes in discussion of public innovation. Furthermore, the instruments, machinery and equipment innovations that I observed in this dissertation were in an institutional field dominated by the norms of open science—norms that favour disclosure and recognition, not secrecy (Merton, 1957, 1973).

Another possible explanation for the limited research on public innovation in goods is that it might only occur in rare contexts. If these contexts are relatively unknown, then the lack of research on public innovation in goods may be a simple oversight. However, several scholars have demonstrated that they are anecdotally aware of this phenomenon in defense-security contexts (Gallouj et al., 2013; Mazzucato, 2013a) and in public medical/health care contexts (Hartley, 2005; Windrum & Koch, 2008). Furthermore, there were signals in the literature (i.e., Riggs & von Hippel, 1994; Spital, 1979; von Hippel, 1976, 1988) pointing toward the presence of public innovation in goods in the context of scientific instrumentalities. Defense, health care, and science are not rare or unstudied contexts.

These two alternative explanations for the lack of research on public innovation in goods—that it is secret or that it is rare—do not account for many instances where public innovation in goods is mentioned in the literature but not incorporated into empirical work (e.g., De Vries et al., 2016; Halvorsen et al., 2005; Hartley, 2005; Koch & Hauknes, 2005; Mazzucato, 2013a; R. M. Walker et al., 2002; Windrum & Koch, 2008). Further to this, it is probable that public innovation in goods is understudied because it is a form of dark innovation. This phenomenon is not overly secret or rare. Rather, it is partially obscured by market-oriented theoretical and analytical frameworks.

There is also an alternate explanation for my funding that warrants discussion. I have found that, in this innovation system, eight public organizations produced innovative goods over the past 5 years. However, some readers might argue that I have observed process innovations, not product innovations—and process innovations in public service organizations are relatively well-studied (see De Vries et al., 2016; Gallouj et al., 2013; Hartley, 2005; Røste, 2005; R. M. Walker, 2014; R. M. Walker et al., 2002). It is common to dismiss public innovation in goods as something less than it is: as process innovation, rather than product innovation. For example, von Hippel and his colleagues labelled their observations as “user-innovation” even through the scientists they observed were clearly doing much more than simply using new process equipment (Riggs & von

Hippel, 1994; Spital, 1979; von Hippel, 1976, 1988). These scientists were also building multiple copies of their new scientific instruments and providing these to other scientists in external organizations (von Hippel, 1976). But von Hippel considered this to be a “pre-commercial” activity (von Hippel, 1976)—taking place outside the market—and therefore not product innovation. Robert Dalpé (1994) has drawn a similar conclusion based on Canadian patent data, which he says “reveal government ownership of a sizeable number of patents in various industries involved with the *government market* [emphasis added]” (p. 76). He characterized these as the by-products of public service delivery and he suggested that these innovations eventually come to rest on the private-sector side of a public procurement process (Dalpé, 1994). Also, in Chapter 1, I discussed two studies (i.e., Arundel & Huber, 2013; Bugge et al., 2011) that report data on public innovation in goods but suggest that these may have been components of service innovations—i.e., process innovations that enabled services innovation. In sum, then, the prevalent argument is that public organizations are outside the market and so any goods they might develop are merely process innovations. These goods might not qualify as product innovations because they are not introduced “on the market” (OECD, 2005, p. 47) until they have been sold by a private sector manufacturer.

My research supports a counterargument. Attributing product innovations to the market, and thinking that public organizations are outside the market, keeps such innovation in the dark. To achieve a different perspective on public innovation, I used a systems of innovation approach and framed innovation as an interactive learning process. I did not focus exclusively on market transactions because the “theoretical core” of the innovation systems approach is the learning interaction (Lundvall, 2013, p. 32), not the market transaction. In my interview instrument, I allowed capital equipment and technical services to be provided by one organization and acquired by another organization via market and non-market exchanges. In this way, I defined product innovations as any goods or services that were produced by one organization and brought into use by any other organization. My definition of innovation conforms with only part of the language in OECD's third edition *Oslo Manual.* The manual—which is widely used by statistical agencies and researchers—does say that innovations must be "implemented" and "brought into use," but I have joined Gault (2018) in arguing that it goes one step too far by also suggesting that this use must be "on the market" (OECD, 2005, p. 47).

I assert that a market-based definition of innovation creates a double-standard. It allows any new goods sold by a private company to be immediately labelled as "product innovations." These goods then become "process innovations" in any type of customer organization—including a public organization. However, a market-based definition also means that new goods provided by one public organization to another will continue to be labelled as "process innovations" if they have not entered the market. Large volumes of such goods could be produced and disseminated by a public organization, but they would not be considered "product innovations" until they are bought and sold on the market, or—in the case of the strictest neoliberal definitions—until they are produced and sold by a private company. Rather than reifying the market—treating it like a real and special place—my approach includes various market transactions among many forms of interactive learning. This has allowed me to observe innovations that are produced by public organizations and brought into use through non-market transactions. This opens up a space for new and different understandings of public innovation.

While conducting the interviews for this study, I asked each organizational key informant to categorize their organization's outputs and then to categorize their organization's process innovations. Responses indicated that the outputs from 8 out of 14 public organizations included instruments, machinery and equipment; these outputs or products became process innovations when they were introduced into recipient organizations. I asked a separate question about process innovation and 13 out of 14 public organizations reported the introduction of new machinery or equipment into their processes. By rejecting a market-oriented definition of innovation, I observed goods that were being implemented as process innovations by public organizations, but more importantly, I also observed goods that were being produced by public organizations. While I concede that the production of innovative goods is not the primary activity of most public organizations, my results support the contention that such innovations are not exclusive to the private sector.

In Chapter 1, I note that there is very limited research investigating public innovation in goods. My results have now shown that the phenomenon exists, and that it can be studied. So far in this chapter I have focused on the simplest yet most important contribution of this dissertation: expanding the scope of research into the entrepreneurial state by removing public innovation in goods from the realm of dark innovation. In the following sections I discuss contributions that arise from my network analysis and I make specific recommendations for future research into this phenomenon.

The dark innovation challenge: Methodological contributions. My assertion that public organizations produce innovative goods underscores the importance of my methodological contributions. I needed to make careful decisions with respect to my theoretical framework, my choice of empirical context, and my analytical framework. These decisions allowed me to develop a research design that did not automatically exclude the possibility of public innovation in goods. The adjustments I made in my analytical framework and research methods fit together to produce methodological contributions that can be transferred to future research. Such methodological contributions are likely to arise from any research into dark innovation, because dark innovation is only unobservable due to the current limitations of our social science instrumentalities (B. Martin, 2013, 2016). The theoretical contributions from this dissertation were made possible by assembling a “flashlight” that was capable of searching outside the neoliberal spotlight. Martin (2013, 2016) identified the need for methodological contributions like this as one of his grand challenges in innovation studies.

Illuminating dark innovation. To achieve this methodological advance, I took advantage of several theoretical tools that are underutilized in innovation systems research. Many innovation scholars use the term “institution” to separate public organizations from private companies (Edquist & Johnson, 1997). Instead of using this term in this way, I followed the work of Edquist and Johnson (1997) and North (1990) to clearly differentiated between the components of an innovation system: the organizations, their learning interactions, and the institutional field. Conceiving the system as made up of these components allowed me to include PROs and other public organizations under the same umbrella as private companies—I considered them all to be organizations.

Overcoming a market-orientation meant framing the innovation system as a range of different learning interactions, not all of which involved market exchanges. While it is more common to conceptualize interactive learning as a set of market transactions between users and producers (Lundvall, 1988), this encourages a focus on the private sector. Because my channels of interactive learning framework (Table 2 and Figure 3) does not make a distinction between users and producers, or between public and private organizations, I was able to ask all organizational key informants the same questions during data collection.

Finally, because I approached my research with a systems of innovation framework, I overcame key limitations of linear and chain-linked models. I conceptualized and then analyzed innovation at a system-level—as the sum of many interdependent dyads. I thereby produced a dataset with which I could test hypotheses about the importance of public organizations.

Taken together, these moves form one methodological contribution: I have shown that, contrary to Mazzucato's (2013a) arguments, the systems of innovation approach is not inherently blind to the entrepreneurial state. The innovation systems literature in fact already contains the necessary theoretical and analytical concepts for overcoming neoliberal biases; nonetheless, I needed to take exceptional care in my assembly of theory and method.

***Specifying system boundaries*.** Two additional methodological contributions can be drawn from my analytical framework and research method: a contribution related to boundary specification, and one related to system-level analysis. As I argued in Chapter 4, innovation system boundaries are typically taken for granted: care must be taken in defining regional boundaries (Doloreux & Parto, 2005) and in defining the boundaries around a socio-technical system. The regional boundary for this study was relatively easy to identify and was confirmed by expert key informants. However, I could not use a standard approach for identifying the socio-technical—or sectoral—boundary. Such boundaries are typically identified based upon statistical agencies' product classification systems. I could not use this approach here because these classification systems separate public organizations from private companies, even when their products are similar. Instead, I combined insights from the literature on innovation systems and from the literature on network analysis to produce a theoretically-rigorous boundary specification. My boundary specification approach not only allowed public organizations to be part of the system, but also stayed true to the theoretical core of an innovation systems approach—I used the concept of interactive learning and created a boundary specification that was primarily "activity-based" (Laumann et al., 1983). If innovation studies has truly advanced from a focus on innovation-as-outcomes to an understanding of innovation as an interactive learning process (Fagerberg et al., 2013; Lundvall, 2013), then the continued use of product-based sectoral boundaries may be inappropriate. Activity-based boundary specifications may be more appropriate to a processual understanding of innovation. Furthermore, I demonstrate in Chapter 4 that an activity-based boundary is entirely consistent and reconcilable with a conceptualization of innovation systems as institutional fields that are shaped by socio-technical regimes (Breschi & Malerba, 1997) and regional geographies (Asheim et al., 2011; Cooke, 2001; Doloreux & Parto, 2005). Following on my work in Chapter 4, then, future innovation systems research can engage directly with questions of boundary specification.

From linear to systems analysis. My third methodological contribution is the use of network analysis for revisiting insights from linear innovation models. I agree with von

Hippel and his colleagues that scientists are the locus of innovation—the most important actors—for scientific instruments (Riggs & von Hippel, 1994; Spital, 1979; von Hippel, 1976, 1988). But I dispute the validity of the linear innovation model they used in their research. Over the course of several chapters, I introduced an innovation systems theoretical framework and then a network-based analytical framework. My first hypothesis was that the conclusions from von Hippel *et al.* (Riggs & von Hippel, 1994; Spital, 1979; von Hippel, 1976, 1988) would hold under a network analysis using a static node-based conceptualization of importance: degree centrality. My fourth hypothesis was based on a more dynamic and network-wide measure of importance: distance-weighted fragmentation. In both cases, I found that the conclusions derived from a linear model did not translate directly to a systems model. As might be expected, the greater complexity of a systems model means that my results are different than those of von Hippel *et al.* (Riggs & von Hippel, 1994; Spital, 1979; von Hippel, 1976, 1988).

In the simple linear model that was used for early research on scientific instrument innovation there were only two actors for each product innovation: a user and a producer. This naturally led to the conclusion that one type of actor was more important than the other. There could only be one locus of innovation, and it had to be either the user or the producer. The advantage of a systems approach is that it can overcome the dichotomies embedded in linear (e.g., Myers & Marquis, 1969), chain-linked (e.g., Kline, 1985; Kline & Rosenberg, 1986), and even symbiotic (e.g., de Solla Price, 1984; Rosenberg, 1992) understandings of innovation relationships. My data collection process was open to any organizations that might be identified by system-level experts. As a result, my data included organizations that use and produce scientific instrumentalities—PROs and private companies, plus a third type of organization—public organizations that supported the production and use of scientific instrumentalities. In my tests of hypotheses 1 and 4—based on static (H1) and dynamic (H4) conceptualizations of importance in a network—I found that the locus of innovation was not confined to any one of these three types of organization. Instead, the most important organizations in the network were distributed across the two categories of public organizations. My data suggest that there are multiple loci of innovation in this particular innovation system.

Network analysis is thus a valuable tool for advancing toward more complex understandings of innovation. While it is true that scholars already know that these methods have considerable potential for innovation studies (Bergenholtz & Waldstrøm, 2011; van der Valk & Gijsbers, 2010), my contribution shows how network analysis of innovation systems can capture additional complexity and nuance that may be absent from linear analyses. Degree centrality and other point-based network measures can be used to identify multiple loci. However, I believe that the greater promise for network analysis of innovation systems lies in the use of dynamic network-wide measures—such as distance-weighted fragmentation. Such measures have not yet been widely deployed in economic geography (Glückler & Doreian, 2016) or innovation studies (Bergenholtz & Waldstrøm, 2011), although Giuliani (2013) has made some great strides on this path. My use of distance-weighted fragmentation is a further advancement. At the end of Chapter 3, I identified the future potential for fragmentation and robustness analyses of innovation systems. Thus far, such concepts have been applied in qualitative analysis (Ferrary & Granovetter, 2009; Powell et al., 2012). The quantitative methodological tools I have introduced here align with the theoretical direction of the field, and promise to help with a shift in thinking from dyads and dichotomies toward complexities and systems. The greatest risk in the use of these methods is that they are highly sensitive to anything more than minimal levels of nonresponse.

Scientific instrumentalities: Expanding the evidence base.

Public organizations as anchor tenants**.** Earlier, I introduced the concepts of robustness and fragmentation because the historical evidence was pointing toward a particular way that PROs had been important for this innovation system. The historical evidence suggests that four PROs—the Naval Research Establishment, the Nova Scotia Research Foundation, Dalhousie University's Oceanography Institute/Department, and the Bedford Institute of Oceanography—may have been anchor tenants during the formation of Nova Scotia's ocean science instrumentalities innovation system. Where anchor tenants are typically defined in terms of the functions they perform for a regional innovation system—i.e., knowledge spillovers and attraction of firms (Agrawal & Cockburn, 2003; Feldman, 2003; Niosi & Zhegu, 2010)—I considered the ways in which an interactive learning network might be structurally-dependent upon its anchor tenants. I built upon the work of Ferrary and Granovetter (2009) and Powell et al. (2012) to develop a theoretical proposition regarding the system-wide effect of losing an anchor tenant. As I discuss above, I used a measure of distance weighted-fragmentation and tested a hypothesis about the structural effects of losing PROs from the system. The focus on PROs proved overly simplistic. However, I did find that this particular interactive learning network would experience greater average fragmentation upon the removal of a public organization versus a private company. It would therefore be problematic to conclude that a small group of PROs have been anchoring this system over the past 5 years. A more appropriate conclusion is that a network of public organizations may be collectively responsible for the structural cohesion of this innovation system. Public organizations appear to anchor this system. This conclusion responds directly to my research question—“how important are public organizations for scientific instrumentality innovation?”—and advances the concept of anchor tenants as important for the structural cohesion of regional innovation systems.

Note, however, that there appear to be two very different anchor tenant roles performed by the public organizations in this system. In the first case, there are the PROs, all of which produce new research and many of which also produce new scientific instrumentalities. Secondly, the system also includes public support organizations. There were five such organizations in the network (see Table 10). These are organizations that do not produce research themselves, but provide coordination, networking, funding, and training functions to the innovation system. The Advanced Diploma in Oceans Technology (ADOT) program at NSCC Ivany Campus is a specialized training program that provides students with the necessary skills to work as technicians in this system. The Fundy Ocean Research Centre for Energy (FORCE) located in Parrsboro is a not-for-profit consortium that manages Nova Scotia’s tidal energy test facility in the Minas Passage. The Institute for Ocean Research Enterprise (IORE) is a not-for-profit organization that facilitates relationships between PROs and private companies, and is also a lead partner in the Centre for Ocean Ventures & Entrepreneurship (COVE) facility being developed in Dartmouth. The Marine Environmental Observation Prediction and Response (MEOPAR) Network is a not-for-profit corporation headquartered at Dalhousie University that supports nation-wide research partnerships through funding from the

Government of Canada's National Centres of Excellence (NCE) program. And finally, the Offshore Energy Research Association (OERA) of Nova Scotia is also a not-for-profit organization that facilitates and funds research partnerships. Its focus is on offshore energy and environmental research and it is funded by the provincial government. In sum, these five public organizations support the functioning of this scientific instrumentalities innovation system. Public support organizations like these are not discussed in the existing literature on scientific instrumentality innovation. In the next two subsections, I ask why this type of organizations might not have been previously identified in the literature on scientific instrumentality innovation and then I expand my discussion on the role of these public support organizations versus the role of PROs in this system.

Support organizations and New Public Management. There are two explanations for the absence of these public support organizations from the existing literature on scientific instrumentality innovation. I have already discussed the first of these: a systems lens was needed to observe more than two roles. The theoretical and analytical frameworks used in earlier research about scientific instrumentalities focused on two-role relationships. The linear models used by von Hippel and his colleagues focused on users and producers (Riggs & von Hippel, 1994; Spital, 1979; von Hippel, 1976, 1988). Discussions about scientific instrumentality innovation under the chain-linked model dichotomized research and development roles (Kline, 1985; Kline & Rosenberg, 1986), and dichotomies were also used in STS discussions of science-technology symbiosis (de Solla Price, 1984; Gorm Hansen, 2011; Rosenberg, 1992). My shift from a linear to a system-level analysis was a prerequisite to observing a third role—the role of public organizations that support science—in scientific instrumentality innovation.

However, I am not convinced that this third role would have been present in 1976, even if von Hippel had used a systems approach. I believe that the presence of these organizations is best explained by the rise of New Public Management (NPM). In Chapter 3, I introduced NPM as a set of widely adopted neoliberal public policy reforms (Hood, 1991; Lorenz, 2012) that have been connected with decades of changes in Canadian science policy (Atkinson-Grosjean, 2006). One element of the NPM agenda is particularly useful in understanding why my results differ from earlier studies of scientific instrument innovation: the “shift to disaggregation of units in the public sector” (Hood, 1991, p. 5). Sociologist of science Janet Atkinson-Grosjean (2006) has argued that the NPM-inspired reorganization of public science in Canada was punctuated by the establishment of the Networks of Centres of Excellence (NCE) program by the Government of Canada in 1988 (Atkinson-Grosjean, 2002, 2006; Fisher, Atkinson-Grosjean, & House, 2001). MEOPAR—one of the five public support organizations in my dataset—is one of 44 present-day NCEs across Canada. Atkinson-Grosjean (2006) has argued that the NCE program was a key means by which the Government of Canada introduced neoliberal ideals and NPM reforms into public science. Over time, the NCE program instituted “structural changes” that were “reminiscent of organizational and managerial innovations implemented in the late 1870s by the German dye manufacturing industry” (Fisher et al., 2001, p. 317)—i.e., specialization, division of labour, and cooperative team/network structures. The governments of Canada and Nova Scotia both support many similar network organizations today, such as FORCE, IORE, MEOPAR, and OERA. In this way, some of the governance and management of science has been disaggregated from PROs into separate organizations. Remember that the historical records discussed in Chapter 3 placed these functions within the operations of the BIO campus and the NSRF—both had internal units devoted to managing relationships with external learning partners. It is therefore plausible that NPM reforms led to some disaggregation of science management and governance functions from the work of scientific investigation. The separation between NSCC's ADOT program and its Applied Oceans Research Group might also be explained by NPM's disaggregation doctrine. One of my dissertation's theoretical contributions is the identification of this third role—an organizational support role—in scientific instrumentality innovation.

Public organizations as innovation agents and quartermasters. By dropping the ADOT training program for a moment, and focusing on the other four public support organizations, I can highlight a further theoretical contribution from my research. FORCE, IORE, MEOPAR, and OERA are all engaged in the kind of "embedded network governance" that Erica Fuchs (2010) has attributed to DARPA in the period after 1992. Fuchs (2010) makes an important contribution, identifying what she considers to be "a new form of technology policy, in which embedded government agents re-architect social networks among researchers so as to identify and influence new technology directions in the U.S." (Fuchs, 2010, p. 1145). My research suggests that this function is not unique to DARPA. Indeed, this function may be quite widespread if it is indeed driven by the disaggregation doctrine of NPM and the subsequent era of "networked governance" in the public sector (Hartley, 2005). Atkinson-Grosjean (2006) described the NCE program in Canada as a means by which "the state attempts to steer the research agenda and institutionalize processes of agenda building" (p. 34). This is similar to the way that Fuchs' (2010) describes DARPA's embedded network governance function. Linking the concept of embedded network governance with the literature on NPM suggests that such organizations may be found across the many countries that engaged in NPM reforms, opening an important avenue for future research on the entrepreneurial state. Linking these ideas also suggests that the critique of NPM reforms (Hood, 1991; Lorenz, 2012) might extend to embedded network governance organizations.

At the end of Chapter 3, I combined an understanding of this system's historical context with my insights about scientific instrumentality innovation leading to new metaphors that could be used when thinking about a scientific instrumentality innovation system. I suggested that PROs might be considered the anchors and private companies might be considered the "quartermasters"—providing the necessary equipment for scientific research. However, my results now suggest that these role assignments may be insufficient. The support I found for hypotheses 1b and 4b does suggest that public organizations might be performing a type of anchor tenant function in this innovation system. But I also found that multiple public organizations were quartermastering: they were actively engaged in a range of product innovations. It is therefore possible to think of some public organizations as quartermasters, alongside private companies. Other public organizations in this system—the public support organizations—were performing a third role. Here, it is useful to think about two different kinds of quartermasters. There is the army quartermaster function I introduced in Chapter 3: the one that performs a product innovation function. But in navies, the quartermaster is chief navigator and master of the quarterdeck—the room from which the Captain and helmsman control the ship. Thus, some public organizations in this system are like the naval quartermasters:

they manage, govern, and/or facilitate network relations. This is not product innovation or process innovation; rather, it is an organizational innovation function.

In the research question at the heart of this dissertation, I asked about the importance of public organizations for scientific instrumentality innovation. In the system I studied, I found public organizations to be anchor tenants—the loci of innovation in the system. But because the network contained two broad types of public organizations—PROs and support organizations—I have consequently developed a more nuanced answer to my research question. I propose that public organizations are important for scientific instrumentality innovation because they are both system anchors and quartermasters.

The importance of private companies. While this work aims to increase attention on public innovation, I do not intend to minimize the importance of private companies. All the private companies that participated in my research reported product innovations, so it is appropriate to continue thinking of them as quartermasters for science—i.e., the suppliers of capital equipment and technical services. And yet, my data suggest it is inappropriate to assume this quartermaster role is more passive than the role performed by public organizations. Indeed, earlier research on scientific instrumentality innovation (de Solla Price, 1984; Riggs & von Hippel, 1994; Rosenberg, 1992; Spital, 1979; von Hippel, 1976, 1988) may have over-simplified the private sector role. To explain this point further, let me illustrate the functions of these roles in terms of *epistêmê* and *technê*.

I have already pointed out that public organizations in this system are proficient in the production of highly technical devices. At least 8 of 9 PROs were engaged in producing both *epistêmê and technê*. And it is also important to note that private companies in this system are proficient not only in *technê*, but also in the *epistêmê* of ocean science. This is recorded in the types of innovations reported in Table 11. Five of 11 private companies that participated in this research had produced the kinds of reports, information, documents or manuscripts that might be more commonly expected of the PROs that produce *epistêmê*. Five companies also reported delivering science-like services including data collection, processing or analysis. I therefore conclude that the private companies in this system are not passive quartermasters. Indeed, many of these companies engaged in the *epistêmê* of ocean science.

My dataset therefore suggests that *epistêmê* is not the exclusive domain of PROs and *technê* is not the exclusive domain of scientific instrumentality companies. This is contrary to the conclusions one might draw from the writings of de Solla Price (1984) and Rosenberg (1992). They described *epistêmê* and *technê* as separate but mutually-dependent knowledge bases for scientific instrumentality innovation. Because most organizations in my dataset have proficiencies in both the *epistêmê* and *technê* elements of ocean science, I have identified a more complex “systemic interdependence” (Lundvall, 1988, p. 350) that was only implied by earlier research in this context (de Solla Price, 1984; Gorm Hansen, 2011; Rosenberg, 1992). With respect to this interdependence, I contend that the relationships between PROs and companies in this system are productive because the parties are sufficiently proficient in both the *epistêmê* and *technê* of ocean science. In other words, an organization may have substantial expertise in *epistêmê*, but this does not mean the organization is inept in *technê*—or visa versa. Within this system there does not appear to be a clear division of responsibilities with respect to the *epistêmê* and *technê* of ocean science. I therefore propose that the socio-technical regime around scientific instrumentalities may be a bridge between what some scholars consider to be separate systems of science and technology (e.g., Kaufmann & Tödtling, 2001) and between analytic and synthetic knowledge bases (e.g., R. Martin, 2012, 2013; R. Martin & Moodysson, 2011a). Since most public and private organizations in this system appear to cross this boundary, the system itself might be in a brokerage position.

Further, my results imply that scientific instrumentality companies may be more multidimensional than prior research suggests (i.e., de Solla Price, 1984; Riggs & von Hippel, 1994; Rosenberg, 1992; Spital, 1979; von Hippel, 1976, 1988). The prior literature suggests that private companies have limited roles as producers of scientific instruments (Riggs & von Hippel, 1994; Spital, 1979; von Hippel, 1976, 1988) and it says that these companies primarily provide the "private goods of the scientific research industry" (Rosenberg, 1992, p. 381). I therefore hypothesized that the flow of capital equipment and technical services would be the most important channel for interactive learning in scientific instrumentalities. But, as I describe in Chapter 6, this was an oversimplification of the interactive learning network. The most important relationships in this network were indeed predicted by capital equipment and technical service interactions. However, informal knowledge sharing and R&D partnerships were stronger predictors of the most important relationships. Notice how these top two predictors of the most important learning interactions were bidirectional channels. Notice also that my channels of interactive learning framework—adapted from De Fuentes and Dutrénit (2012)—provided a significant prediction of the most important relationships in the network, whereas commonly used variables—geographic proximity, organizational age, size, and R&D intensity—did not. Consistent with prior research, multiple channels of interactive learning were coupled together in a “dynamic interaction” (Azagra-Caro, Barberá-Tomás, Edwards-Schachter, & Tur, 2017), although “formal knowledge sharing” was not an important component of the model. For ocean science instrumentality innovation in Nova Scotia, my results suggest that it might not be appropriate to narrowly focus on encouraging innovation via procurement policies. One might be inclined to focus on procurement after reading Rosenberg (1992), Dalpé, DeBresson, and Xiaoping (1992), or Dalpé (1994). However, my results support the view that interactive learning in this context is more multidimensional.

My results are therefore consistent with some prior descriptions of scientific instrumentality relationships, particularly those that describe symbiosis (de Solla Price, 1984; Gorm Hansen, 2011; Rosenberg, 1992). I found that the majority of relationships between PROs and companies were multiplex and bidirectional, pointing to symbiosis and mutual dependence between public and private organizations. But, this symbiosis does not imply a division of responsibilities; instead, it may be a function of overlapping proficiencies in both *epistêmê* and *technê*. If this is the case, scientific instrumentality innovation may be a useful context for advancing research into knowledge bases for innovation (R. Martin, 2012, 2013; R. Martin & Moodysson, 2011a).

Policy Implications

Although “ocean technologies” have been identified as an industrial policy priority by all three levels of government in this region (Atlantic Coastal Zone Information Steering Committee, 2006; Government of Nova Scotia, 2012; Greater Halifax Partnership, 2012), only a minimal evidence base is currently available with respect to ocean technology innovation in the region. Prior policy research in this region has produced a basic understanding of ocean technology products (Atlantic Coastal Zone Information Steering Committee, 2006), a map of global ocean technology value chains (Gereffi, Brun, Lee, & Turnipseed, 2013), and an understanding of local human capital requirements (Institute for Ocean Research Enterprise, 2015). Outside of this region, the OECD has published a policy paper on the future of the global ocean economy (OECD, 2016). My policy contribution is different from these prior reports in that I am not focused exclusively on industrial policy. I add to the discussion of industrial policy in this region by linking it to policy matters that are sometimes treated separately—in the realm of science policy (Amankwah-Amoah, 2016; Bianchini & Llerena, 2016; Salazar & Holbrook, 2007). This dissertation simultaneously speaks to issues of concern for both industrial policy and science policy.

The innovation studies literature often analytically separates science, technology, and innovation (STI) policies (Dodgson, 2000; Lundvall & Borrás, 2005), however these policy realms normally overlap in practice (Dodgson, 2000). Problems can arise when these policy realms diverge (Amankwah-Amoah, 2016; Bianchini & Llerena, 2016). In Canada, the cohesiveness of STI policies is influenced by the constitutional separation of powers between federal and provincial governments (Sá, 2010; Salazar & Holbrook, 2007). The Government of Canada has a long history of active science policy (Fisher et al., 2001; Sá & Litwin, 2011; Salazar & Holbrook, 2007), but most provincial governments—including Nova Scotia—engage in limited science policy effort (Sá, 2010; Salazar & Holbrook, 2007). Meanwhile, technology and innovation policies—defined via industrial policy in Canada—are orchestrated by complex regional policy networks (Salazar & Holbrook, 2007). Salazar and Holbrook (2007) argue that neither federal nor provincial government “can afford to renege on its responsibilities” to engage cooperatively in science, technology, and innovation policy. Coordination—via multi-level governance—is required to overcome system failures in Canadian regional innovation systems (Salazar & Holbrook, 2007).

In Chapter 3, I noted a potential failure in Nova Scotia’s ocean science instrumentalities innovation system. Five years ago, substantial federal cuts were made in ocean science across Canada (Bailey et al., 2016; Turner, 2013) at the same time as regional policy networks were prioritizing investments in ocean technology innovation via industrial policy (Government of Nova Scotia, 2012; Greater Halifax Partnership, 2012). Ocean science and ocean industry policies were moving in opposite directions. My results suggest that this disconnect may have been problematic because, in the interactive learning network that I observed, the loss of a public organization would cause greater fragmentation to the network—on average—than the loss of a private company (see results for hypothesis 4). This suggests that the innovation system may be structurally dependent upon public organizations. Furthermore, I found that the majority of interactive learning relationships between PROs and private companies in this network were symbiotic (see results for hypothesis 2). This suggests that it may be important to connect public policies in support of private companies in this system (i.e., industrial policies) with policies that affect PROs and public support organizations (i.e., science policies).

In 2016, the Government of Nova Scotia announced plans to more fully engage in regional science policy networks via the establishment of a new public organization—

Research Nova Scotia (Grant, 2016)[26]. This is a potentially promising step toward resolving the disconnect between ocean science and ocean industry policies; the Government of Nova Scotia may be becoming more active in regional science policy networks. Meanwhile, the Government of Canada has begun to reinvest in science over the past year. An *Advisory Panel for the Review of Federal Support for Fundamental Science* has advised Parliament on future directions for science policy in the country (Naylor et al., 2017). However, the report from this panel only briefly mentions funding for "research tools and instruments" (Naylor et al., 2017, p. 126 and 176). As reinvestments in science are being made, federal policymakers might consider opportunities for innovation in scientific instrumentalities. For example, it might not be appropriate to completely outsource technical expertise via procurement from PROs to the private sector. NPM reforms have included widespread outsourcing of activities from public organizations to the market (Hood, 1991). However, further to my results for hypothesis 3, the capital equipment and technical services channel was not the strongest predictor of the most important relationships in this network. Informal knowledge sharing, R&D partnerships, and HR flows were stronger predictors. Policy makers should carefully consider whether particular procurement practices might encourage interactive learning for scientific instrumentality innovation or whether they might create arms-length relationships between companies and public organizations. Similarly, it may be problematic for policy to focus on intellectual property rights channels for this system

[26] At the time of this writing (February 2018) some preliminary steps had been taken toward establishing Research Nova Scotia (Government of Nova Scotia, 2017).

since the presence of an IP interactive was a negative predictor of the most important interactive learning relationships in this network. This finding reinforces a concern about Canadian science policy that has been raised by Creso Sá and Jeffrey Litwin (2011). With respect to federal science policies and university research, they say,

> The emphasis on commercialization has some potential drawbacks…overall, this emphasis on producing short term commercial outcomes steers university research towards near-term applications, and may not necessarily lead to deep relationships between universities and firms or to building capacity in the firms (Sá & Litwin, 2011, p. 432).

I observed deep relationships—i.e., multiplex and bidirectional learning interactions—within the ocean science instrumentality innovation system in Nova Scotia (see results for hypothesis 2). To continue this interdependence, policy might support a mix of bidirectional learning channels between public and private organizations. To enable these symbiotic relationships, it might also be important for public organizations to have their own in-house technical capacities—so that they are not technically inept.

Overall, my work reinforces the importance of federal investments in science for ocean science instrumentality innovation in this region, and the importance of provincial government participation in regional STI policy networks. I have also expanded on Mazzucato’s policy contributions (2016; 2013a, 2013b, 2013c, 2016; 2016) by showing that the entrepreneurial state’s market-creation powers may include the ability to develop novel new technologies—i.e., scientific instrumentalities. Furthermore, there are some indications that the entrepreneurial state may have more ability to govern innovation networks—and thereby create new markets—than previously thought. NPM reforms may have led to a proliferation of public support organizations dedicated to network governance of public science. It is possible that these disaggregated units may be in a better position to perform network brokerage functions. However, future research should ask questions about the impact of NPM on the effectiveness of public science. For example, in my history of the BIO (see Chapter 3), I briefly mention the shift from a large internal technical unit to an industry liaison officer, which may have been an NPM-style outsourcing of technical competencies. Such moves might not be beneficial for the symbiotic nature of interactive learning in this innovation system. Further policy research is needed regarding public innovation in goods, NPM, networked governance, and the entrepreneurial state.

Limitations

Before concluding this work, I must caution readers not to assume that my results are generalizable to other contexts. Achieving generalizability means designing research in such a way that the participants represent a broader population. By demonstrating the representative nature of a sample, researchers argue that their findings are generalizable across an entire population. This logic is based upon a nomothetic approach borrowed from the natural sciences. The goal of nomothetic research is to establish general laws that can describe and predict a phenomenon. As Lincoln and Guba (1985) explain, "generalizations are assertions of enduring value that are context-free" (p. 110). The drawback is that details of each case are lost in the generalization.

The alternative logic, which I have used here, is an idiographic approach common to the humanities. Burrell and Morgan (1979) describe an idiographic approach as one that "places considerable stress upon getting close to one's subject and exploring its detailed background and life history" (p. 6). In short, the goal of an idiographic approach is to specify the details of a case. Case studies are therefore inherently idiographic

(Bryman et al., 2011): they are useful when the researcher is more interested in the details of one or more cases than in the generalizability across all cases. A true idiographic approach does not attempt to claim external validity via generalizability. The case study is not treated as a sample of one.

Lincoln and Guba (1985) proposed an alternative standard for evaluating the external validity of idiographic case studies: transferability (Lincoln & Guba, 1985). Where generalizability means demonstrating that one's empirical material is representative of other contexts, transferability means demonstrating that one's findings are applicable to other contexts. Lincoln and Guba (1985) suggest that transferability is established through the contextual details provided in a study—such as those I provide in Chapter 3. This is what Geertz (1973) referred to as "thick description." These details help the reader to evaluate similarities and differences between her context and the research context. The reader is therefore armed with all necessary information with which to determine the transferability of the research findings. The notion of transferability accepts that there are limits to the external validity of a case study but still attempts to establish theoretical generalizations that may apply under certain similar contexts. This entire work was designed to achieve transferability rather than generalizability. To this end, I have focused on revealing and describing a particular phenomenon, in a particular context. I can not yet say whether my results are generalizable to other contexts, but I can assert that they open new ways of thinking about research and policy.

Further to this point, I raise three specific cautions regarding generalizability and transferability. First, it is important to emphasize that the p-values reported in Chapter 6 are not indicative of the probability that a particular observation might generalize beyond this study. Under the QAP network analysis approach, the p-values indicate the probability that the observation might have occurred at random. The p-values represent the proportion of random permutations that yielded values greater or less than the observed values. QAP p-values cannot be interpreted in the same way as a classic significance test. Further discussion can be found in Borgatti et al. (2013). Second, it is important to emphasize that the policy implications discussed above should not necessarily be generalized beyond Nova Scotia's present-day ocean science instrumentalities innovation system. As Lundvall and Borrás (2005) explain, "innovation policy needs to build upon insight in a specific context […] 'best practice' cannot be transplanted from one innovation system to another" (p. 617). The risk here is that the policy implications discussed above may be taken up by organizations whose mandate extends beyond this innovation system to other regions or sectors. Policy makers are urged to consider the limits to the transferability of policy implications.

The third specific point of caution regarding transferability is with respect to jurisdictional differences in the way that one might distinguish between public and private organizations, particularly public and private universities. In Nova Scotia, all PROs—including universities—are public organizations, given the guidance provided by Perry and Rainey (1988). However, "private" universities may be present in other regions. The private versus public nature of universities in the USA has been debated in the legal community (see O'Neil, 1969). Nonetheless, regional differences in the ownership, funding, and governance of PROs are real limits to the transferability of this research.

Several additional limitations have been discussed briefly throughout this dissertation. In Chapter 3, I discussed the limitations imposed by the historical evidence that was available. Most of this evidence was produced by the four PROs discussed in the chapter. Their importance in the historical narrative may be related to their authorship of the archival material. The regional history section of Chapter 3 should not stand alone as evidence that the PROs were serving as anchor tenants in this innovation system. Chapter 3 provided some context with which to begin understanding the institutional environment around this innovation system, and yet my research question and analytical framework (i.e., my use of quantitative network analysis) meant that this study has provided limited qualitative evidence on the institutions that shape interactive learning in this system. Further qualitative research would be helpful here.

In Chapter 5, I discussed the limitations of the fixed list approach for network data collection. The fixed list approach does not account for the open nature of innovation systems. Also, it captures the core of a network but not the periphery (Doreian & Woodard, 1992). Peripheral network positions could be important for creativity and innovation (Cattani & Ferriani, 2008; Kudic et al., 2015), but generally core network positions are more valuable for innovation because they provide better access to knowledge in the network (Giuliani, 2013; Giuliani & Bell, 2005; Kudic et al., 2015; Rank et al., 2006). There is a valid concern that the exclusion of peripheral nodes from a network dataset may introduce bias in certain network measures, however, Doreian and Woodard (1992) have shown that the effect is an understatement rather than a misstatement of the core nodes' centrality in the network. It is nonetheless important to reiterate that the network examined in this dissertation represents the core—not the periphery—of the innovation system.

In Chapter 6, I discussed a further limitation related to the interpretation of degree centrality values. Degree centrality is a common proxy for importance in a network (Borgatti et al., 2013; Gay & Dousset, 2005; Takeda et al., 2008), but high degree centrality scores can also indicate higher propensity to establish network relationships. For this reason, I presented a cautious interpretation of the result for hypothesis 1 (b): the result indicates that public organizations were more connected, on average, than private companies in this network. I was only comfortable drawing conclusions about the importance of public organizations in this network after this result was combined with a dynamic conceptualization of importance—via the results for hypothesis 4(b).

Future Research Directions

Future research on public innovation and the entrepreneurial state. This study is only the first of others that should follow in an effort to address the public innovation in goods gap. My work suggests that taxonomies of public innovation should include a category for goods (like De Vries et al., 2016; Hartley, 2005) as should instruments designed to measure public innovation (further to Arundel & Huber, 2013; Gault, 2018). Furthermore, future adaptations of the general taxonomies of innovation (e.g., Archibugi, 2001; Castellacci, 2008; Pavitt, 1984) should consider public organizations. A new a line of research investigating public innovation in goods could help determine where public organizations fit and how such taxonomies might be revised or expanded. Another potentially fruitful line of research could develop at the intersection of innovation studies and marketing; In Chapter 1, I suggested that innovation studies could benefit from a services-dominant logic like the one found in marketing (Vargo & Lusch, 2004, 2008).

My discussion above also suggests that innovation studies could benefit from further investigation into the ways that private companies might serve as quartermasters for public innovation. This could advance the procurement-for-innovation literature (Dalpé, 1994; Dalpé et al., 1992; Edquist et al., 2000; Edquist & Zabala-Iturriagagoitia, 2012, 2015). The importance of public organizations for innovation systems might be further explored by more advanced applications of robustness analysis. Robustness analysis can be used simulate the effect of removing public organizations from an innovation system—employing a network-based definition of anchor tenants. However, I have cautioned that such analyses are sensitive to high levels of missing data; it is challenging and risky to collect primary data on whole networks.

In short, my research points to a wider range of research questions related to public innovation and to the entrepreneurial state challenge in innovation studies (B. Martin, 2013, 2016). Interesting future research questions include:

– In what other contexts might public innovation in goods be observed? What roles do public organizations play in these contexts? What activities do they perform?
– How might public innovation be constrained through neoliberal discourse? What are the effects of NPM reforms for innovation systems (Røste, 2005)?
– How do procurement-for-innovation policies relate to public innovation in goods?
– In what other contexts might public organizations serve as anchor tenants? What are the implications for our understanding of the roles public organizations can play if they are anchor tenants in some regional innovation systems?

Overall, this dissertation reinforces the argument that public organizations should not remain "conspicuously missing" (Koch & Hauknes, 2005) from analyses of new product and process innovation.

Future research on innovation in scientific instrumentalities. In indicating the importance of public organizations for ocean science instrumentality innovation in Nova Scotia, my work points toward potential for further research on scientific instrumentality innovation. Whereas von Hippel (1988) suggested that the field of scientific instruments was not normal and did not warrant further study, I call for more research into scientific instrumentality innovation. Not only has this context provided a "revelatory" case (Yin, 2009) of dark innovation, but it has pointed to a possible intersection of analytical and synthetic knowledge bases—*epistêmê* and *technê*. The potential importance of this context is reinforced in a very recent study by Shu-Hao Chang (2017), which found the international patent class G01N—measuring/testing instruments for physics—to have the greatest betweenness centrality of all patent classes in a university-industry co-patenting network. Furthermore, there is the decades old observation that the scientific instrumentalities field might be home to some of the world's most radical innovations (de Solla Price, 1984). To these ends, future research could investigate scientific instrumentality innovation in other fields of science, other regional contexts, and with other research questions. These questions might include:

– Are there differences in scientific instrumentality innovation across different scientific disciplines? Do the important interactive learning channels differ from one system to the next?

- What is the role of scientific instrumentality innovation in the emergence of new scientific disciplines?
- In what ways are analytic and synthetic knowledge bases present in scientific instrumentality innovation systems?
- Are regional scientific instrumentality innovation systems connected through global innovation networks (Chaminade & Plechero, 2015; Liu et al., 2013)?
- In what ways do different approaches to science policy influence scientific instrumentality innovation?
- How prevalent is user-innovation (von Hippel, 2005) in the field of scientific instrumentalities?

Furthermore, given my discussion above, I believe it is particularly important to pursue future research regarding the implications of NPM and the (re)organization of science on public organizations' innovation competencies. Clearly DARPA is not the only public support organization that performs an embedded network governance function (Fuchs, 2010), and this point warrants further research.

Future research on research methods and dark innovation. To produce my contributions, I had to align theory, context, analytical framing and research methods such that my research was not constrained to a market-orientation. This allowed me to observe some dark innovation. My methodological contributions can now be used to further advance the dark innovation challenge (B. Martin, 2013, 2016). Most importantly for this challenge, my research reinforces discussion by Gault (2018) on the need to update definitions of innovation (i.e., OECD, 2005). My approach to boundary specification and my adapted channels of interactive learning framework could help to advance the dark innovation challenge. These are both transferable social science instrumentalities that can be used by other researchers to observe innovation outside the market. What else might be learned about dark innovation by using methods like these? Future research can and should continue to develop the necessary social science instrumentalities for studying dark innovation. Tools like the diverse economies framework (Gibson-Graham, 1997, 2005, 2008, 2010) hold considerable potential for revealing additional innovation that might be outside the market.

Glossary

Term	Definition
Adjacency Matrix	A table that represents a network graph using one row and one column for each node. The cells in the table represent relations between each dyad, or pair of nodes.
Bidirectional Ties	Edges that represent relationships where learning/knowledge accrues to both parties.
Degree Centrality	A measure of how well connected a node is within a network.
Distance-weighted Fragmentation	The extent to which distances between nodes in a network increase following the removal of a focal node (Borgatti, 2006).
Edge Betweenness	A measure of how important an edge is within a network, based upon how many pairs of nodes the edge lies between (L. C. Freeman, 1977).
Edges	The linkages between nodes in a network. For an interactive learning network these are the interactive learning relationships.
Industrial Policy	Technology policy and innovation policy are often framed as economic policies (Lundvall & Borrás, 2005) under the umbrella of industrial policy (Edquist & Chaminade, 2006; Salazar & Holbrook, 2007). Industrial policies are those public policies that promote development of private companies in key economic sectors (Salazar & Holbrook, 2007).
Innovation	An on-going process of interactive learning.
Innovation Policy	Public policies that aim to promote the effectiveness of innovation systems (Dodgson, 2000; Lundvall & Borrás, 2005).
Innovation System	A set of organizations that engage in interactive learning within an institutional field.
Institutions	The formal and informal rules found in a geo-political and/or socio-technical environment.
Interactive Learning	Inter-organizational processes that (re)combine knowledge. These processes occur across five channels, which include seven types of relationships.
Interactive Learning Network	A graphical representation of the organizations and interactive learning relationships in an innovation system.
Multiplex Ties	Edges that represent two or more types of relationships.
Nodes	The vertices that may or may not be connected to one another in a network. For an interactive learning network these are the organizations.
Ocean Science	The full range of chemical, biological and physical scientific investigations of the ocean and its contents.

Term	Definition
Organizations	Standalone legal entities or a kind-of-activity units (KAUs). (Includes all legal forms: government departments, agencies, etc.; privately-owned proprietorships, partnerships and corporations; and not-for-profit societies, associations, and corporations).
Public Innovation	Innovation undertaken by public organizations (see a review of the relevant literature in De Vries et al., 2016).
Private Organization	An organization that meets two or more of the following criteria: private ownership, private funding, and market-based social control (Perry & Rainey, 1988).
Public Organization	An organization that meets two or more of the following criteria: public ownership, public funding, and polyarchal social control (Perry & Rainey, 1988).
Public Research Organizations	Organizations that conduct scientific research and meet the public organization criteria above (e.g., government laboratories, universities, and colleges).
Public science	The scientific research activities performed by PROs.
Quadratic Assignment Procedure (QAP)	A combinatorial procedure for resampling matrix data, thereby overcoming the statistical interdependence of the data. It results in a distribution of possible observations that can be compared against observed data to evaluate the probability that the observations would have been observed at random.
Robustness	The ability of a network or system to remain connected when individual nodes or edges are removed.
Science Policy	Public policies that promote research in universities and PROs (Dodgson, 2000; Lundvall & Borrás, 2005). Sometimes referred to as “research policy” (but not in this dissertation).
Scientific Instruments	The machinery and equipment used in the scientific process. In this dissertation, this term is primarily used when referencing research by Eric von Hippel and his colleagues (Riggs & von Hippel, 1994; Spital, 1979; von Hippel, 1976, 1988).
Scientific Instrumentalities	The instruments and techniques used in the scientific process (de Solla Price, 1984).
Technology Policy	Public policies that promote development of key technologies (e.g., ICTs, biotechnology) (Dodgson, 2000; Lundvall & Borrás, 2005).

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Appendix A

Recently published network analyses that consider science-industry interaction

Table A1. Recently published network analyses that consider science-industry interaction (January 2017 to April 2018).

Authors	Context		Nodes	Edges	Notes on Method	Relevant Findings
	Region(s)	Sector(s)				
Arza and Carattoli (2017)[1]	Argentina	n/a	University Research Groups, Firms	Two interactive learning channels: “bidirectional” and “service”.	– Data collected through interviews with university researchers. – Constructed new measure for tie strength. – Econometric modelling.	– For universities, “the bi-directional channel derives primarily knowledge benefits, the service channel derives mainly financial benefits” (p, 829). – Strong ties were related to the bidirectional channel, weak ties related to the service channel.
Bergé, Scherngell, and Wanzenböck (2017)[2]	Europe	Nanotech	Organizations (PROs—incl. universities, and firms).	Scientific co-authorship	– Assembled a dataset from project records. – Developed a measure for “bridging centrality” that approximates for the aggregation of individual-level ties (e.g., co-authorships) to the organizational-level. – Presentation and discussion of network analysis descriptive statistics.	– “The bridging centrality ranking is clearly dominated by non-university public research organizations” (p., 1036). – Technical universities are “important ‘bridges’ between science and industry” (p. 1038). – For studies like this, bridging centrality is a better measure than degree centrality.

Authors	Context		Nodes	Edges	Notes on Method	Relevant Findings
	Region(s)	Sector(s)				
Broekel and Mueller (2017)	Germany	132 different technology-specific networks	Organizations (Uni., firms, research institutes, misc.)	R&D project collaborations.	– Assembled a dataset from project records. – Developed a measure for "bridging centrality" (i.e., "critical links") that is an adaptation of betweenness centrality. – Rare events logistic regression to predict critical links.	– "Critical links particularly bridge institutional boundaries between public (basic) research and (application-oriented) R&D in the private sector" (p. 16).
Calignano and Fitjar (2017)[3]	Apulia, Italy	Mechatronics	Organizations (firms, uni., research centres, associations)	Five types: non-research contracts, research contracts, co-publications, informal contacts, research partnerships	– Collected 2 time-periods of data in one cross-sectional interview (76% response). – Incorporated self-reported edge weights. – Employed SNA descriptive statistics and techniques, plus QAP simple matching.	– Uses QAP simple matching to show that partnership relations persist from T_1 to T_2. – No analysis by organizational type.
Calignano, Fitjar, and Kogler (2018)[4]	Apulia, Italy	Aerospace	Organizations (firms, uni., research centres, associations)	Five types: non-research contracts, research contracts, co-publications, informal contacts, research partnerships	– Collected 2 time-periods of data in one cross-sectional interview (65% response). – Imputation of missing ties. – Incorporated self-reported edge weights. – Employed SNA descriptive statistics and techniques, plus QAP simple matching.	– The cluster association is identified as the critical node. – The network is fragmented (medium to high whole network fragmentation). – Densest network was "informal contacts" with densities of 17% in T_1 and 22% in T_2.

Authors	Context		Nodes	Edges	Notes on Method	Relevant Findings
	Region(s)	Sector(s)				
Chang (2017)	Global (US Patents)	(Patentable)	Bimodal: assignee countries and int'l patent classification codes	Patents	– Assembled a dataset from patent records. – Presentation and discussion of network analysis descriptive statistics.	– The IPC code with the greatest betweenness centrality was G01N – measuring/testing instruments. – "…the focus of [university-industry collaboration] technology development is largely in the fields of measurement and chemistry …[which are] basic sciences, and are often applied in cross-disciplinary research" (p. 112).
K. Chen, Zhang, Zhu, and Mu (2017)[2]	China	n/a	Organizations (gov't research institutes, uni., companies)	Scientific co-authorship	– Assembled a dataset from databases. – Negative binomial regression model to predict scientific performance based on collaboration networks.	– "…research institutes' network positions have a significant effect on their scientific performance, but this effect is inconsistent in different collaboration networks" (p. 17).
S.-H. Chen and Lin (2017)[5]	Taiwan	Biotech	Organizations (firms, uni., public research institutes, research orgs., gov't agencies, hospitals and clinics, and individuals)	R&D relationships (from published sources)	– Mixed method approach that included assembly of network data from public sources (3 time-periods from 2000 to 2012) and 7 interviews to collect qualitative data from university tech. transfer offices. – Presentation of network analysis descriptive statistics.	– The importance of universities and research institutes increased over time. – "Many firms of a smaller size and with lower budgets for R&D relied on academia-industry R&D collaboration" (p. 295).

Authors	Context		Nodes	Edges	Notes on Method	Relevant Findings
	Region(s)	Sector(s)				
Choi (2017)	South Korea	Nanotech	Organizations (firms, uni., public research orgs.)	R&D project collaborations.	– Assembled a longitudinal dataset from databases (2 year intervals from 1999-2007). – Block modelling of firms by industry domain.	– Large firms and gov't research institutes led in the network development phase while small firms joined in the second phase. – No analysis of science-industry links.
Ciapetti and Perulli (2018)	Northern Italian Regions	Advanced Manufacturing	Bi-modal: Research and technology orgs (56% private, 44% public), and technological domains	Self-reported affiliation from orgs to technological domains.	– Collected data from 55 research and tech. orgs (RTOs) via survey (19% response from a population of 293). – Developed an OLS regression model to predict centrality of orgs from a range of independent variables, including the performance of contract research for firms and participation in a collaborative venture.	– "…a business orientation towards firms and a high involvement in collaborations apparently drive the centrality of North Italian RTOs in the R&D network" (p. 208).
Confraria and Vargas (2017)	Latin America	n/a	Organizations (research departments within uni., research institutes, gov't agencies)	5 or more scientific co-publications	– Assembled data for 2-time periods from databases (2004-2008 and 2009-2013). – Presentation of network descriptive statistics. – Econometric modelling to predict intensity of collaboration with industry.	– The best predictors of industry co-authorship are degree and betweenness centralities in the scientific co-authorship network. – 70% of research departments did not co-publish with industry in T1, 78% in T2. – "…in general, collaborations between science and industry, measured as co-publications, are scarce" (p. 23).

Authors	Context		Nodes	Edges	Notes on Method	Relevant Findings
	Region(s)	Sector(s)				
Crescenzi, Filippetti, and Iammarino (2017)[1]	Italy	Patentable	Inventors (academic and business)	Co-patenting.	– Assembled 2 ten-year time-periods of data from patent records. – Measured various distances between pairs (institutional, geographic, organization and social). – Econometric modelling to predict collaboration.	– Due to institutional distance, U-I collaborations are "more difficult to establish," and "qualitatively less productive," but result in better quality patents (i.e., higher forward citations) (p. 747). – Patents in basic science tend to include only academics with U-I collaboration in applied disciplines. – 4.26% of collaborations are U-I pairs.
Latorre, Hermoso, and Rubio (2017)[3]	Walqa Science & Tech. Park, Spain	ICT, biotech, renewable energy	Organizations (firms and uni. research centres)	Self-reported relationship (regardless of type).	– Collected data via survey (96% response). – Presentation and discussion of network analysis descriptive statistics to investigate individual node positions.	– Universities are the "fundamental actors" (p. 1271). – No analysis of interaction between org. types.
Lyu, Wu, Hu, and Huang (2017)[3]	Zhong-guancun, Beijing, China	n/a	Organizations (firms, uni., public research institutes)	Co-patenting.	– Assembled 6 waves of longitudinal data (1995-2014) from patent records. – Presentation and discussion of network analysis descriptive statistics.	– "During the early growth period (early 1990s), university–industry linkages were the pivotal connections of the network, [...] Such effect started to wear off towards the late 1990s" (p. 10). – The key nodes were large state-owned enterprises. The importance of universities increased over time (degree centrality).

Authors	Context		Nodes	Edges	Notes on Method	Relevant Findings
	Region(s)	Sector(s)				
Martin and Rypestøl (2017)[4]	Bergen, Norway	New media	Organizations (firms, public orgs. and non-profit orgs.)	3 types: collaboration for knowledge exchange, labour mobility, indirect monitoring	– Collected data via in-person interviews with firms (roster recall). – Presentation and discussion of network analysis descriptive statistics. – Employed *t*-tests to compare groups of firms (content providers and technology providers) for each type of relation. – Captured relations that extend beyond the region.	– Technology providers more actively collaborated with universities and research organizations than content providers.
Perri, Scalera, and Mudambi (2017)[1]	China	Pharmaceuticals	Patents	Co-patenting	– Assembled data from patent records. – Observations were individual patents and variables capture relational data for each patent. – Econometric modelling to predict geographic dispersion of patent co-authors.	– "…the involvement of academic inventors drives knowledge networks linked to emerging economies to be more internationally dispersed compared to those orchestrated by MNEs" (p. 345). This is particularly true for academic investors from advanced countries. – "…our findings confirm the critical role universities play as growth engines" (p. 349).

Authors	Context		Nodes	Edges	Notes on Method	Relevant Findings
	Region(s)	Sector(s)				
Pinto, Vallone, Honores, and González (2017)	Chile	Patentable	Bimodal network: patents and assignees	Patent co-ownership	– Assembled dataset from patent records. – Presentation and discussion of network analysis descriptive statistics, plus some statistical testing of residency/non-residency in Chile versus technology classes.	– "The results of our study reveal a lack of collaboration between companies and also between science and industry" (p. 64).
Popp (2017)	Global (US Patents)	Alternative energy	Articles and patents	Citations	– Assembled dataset from scientific publication and patent records. – Focal independent variable was org. type: uni., private, gov't research, other. – Multivariate regression to predict citations.	– "…research performed at government institutions appears to play an important translational role linking basic and applied research" (p. 1593).
Roesler and Broekel (2017)	Germany	Biotech	Organizations (firms, uni., public research institutes)	R&D project collaborations.	– Assembled a longitudinal dataset (4 annual periods 2007-2010) from project records. – Employed stochastic actor-based modelling to predict tie formation using organizational proximities and org. types.	– Only 16% of edges were public-private. – Universities were more active collaborators than firms and research institutes and thereby shaped the network over time. – There was an observed preferential attachment effect (based on degree centrality). – Institutional proximity was not a significant predictor of tie formation.

Authors	Context		Nodes	Edges	Notes on Method	Relevant Findings
	Region(s)	Sector(s)				
Rothgang et al. (2017)[4]	Germany	10 sectors	Organizations (unspecified)	Collaborations (unspecified)	– Qualitative analysis/discussion including a network graph. – No discussion of methodology.	– Since the formation of Germany's leading-edge cluster program, "the number of cooperations that bridge the gap between science and business has increased. However, the relative importance of cooperation among public research organizations or between public research organizations and businesses has remained almost unchanged" (p. 10).
Töpfer, Cantner, and Graf (2017)[4]	Germany	Aviation. Biotech, microelectronics, organic electronics, photovoltaics	Organizations (firms, uni., research orgs)	R&D partnerships	– Collected longitudinal data using surveys at 2 time-points (free recall, limited to 10 alters). – Developed a network autocorrelation regression model to predict changes in in-degree over time. – Captured relations that extend beyond the clusters.	– Public funding of cluster projects had differential effects across 5 different networks. – In some sectors, public organizations became more connected, in others they became less connected.

Authors	Context		Nodes	Edges	Notes on Method	Relevant Findings
	Region(s)	Sector(s)				
Xu, Wu, Minshall, and Zhou (2017)	China	3D Printing	Organizations (uni., research institutes, firms)	3 types: scientific co-authorship, co-patenting, and business relations (R&D collab., trading, M&As, and talent exchange)	– Mixed methods: assembled a network dataset from scientific publications, patent records, expert interviews, and secondary industry sources. – Presentation and discussion of network analysis descriptive statistics. – Analyzed 3 types of networks separately and then in a “cross-layer” analysis.	– Based on a qualitative assessment of degree centrality and betweenness centrality, the authors conclude that “…local universities and research institutes are the anchor players in a dense network that provides a strong base of scientific knowledge for China’s 3D printing industry. Surprisingly, they are also the anchor players in the technology ecosystem” (p. 12).

Notes: This table was compiled based on a search (“network analysis” AND (“science” or “science-industry”) since 2017) within the top 10 journals that reference innovation studies (Fagerberg, Fosaas, & Sapprasert, 2012). This initial search yielded eight relevant articles in six journals. Articles were not deemed relevant if they only included data on firms (e.g., Capone & Lazzeretti, 2018) or scientists/PROs (e.g., Tahmooresnejad & Beaudry, 2017) or if there were no relevant organizational-level findings because the analysis was focused on relations between individuals (e.g., Whittington, 2018), product classes (e.g., Taalbi, 2017), or regions (e.g., Lim & Kidokoro, 2017). The search was then expanded to major scholarly databases, yielding 14 additional articles in eight journals. (1) Employs econometric analysis of relational data, not network analysis. (2) Uses an innovation systems approach; (3) Uses an industrial district framework; (4) Uses a clusters framework; (5) Uses a triple-helix framework.

Appendix B

Historiographic Method

To collect the data used in Chapter 3, I began by searching for secondary sources in the digital and card file indexing systems at the Nova Scotia Archives. This led to a total of 70 documents dating from 1944 to 1995, including official and unofficial government reports as well as newspaper and magazine articles. Four PROs figured prominently in these documents: the Naval Research Establishment (NRE), later renamed to Defence Research Establishment Atlantic and now known as Defence Research and Development Canada (DRDC) Atlantic; the federal government's Bedford Institute of Oceanography (BIO); the Nova Scotia Research Foundation (NSRF), which was replaced by the Nova Scotia Innovation Corporation or "InNovaCorp" in 1994; and Dalhousie University's Oceanography Institute, which is now a department. Archival materials were limited for the latter two of these organizations, so I also consulted published histories relating to Dalhousie University (Mills, 1994, 2011; Waite, 1994), a published history of the BIO (Nettleship, Gordon, Lewis, & Latremouille, 2014), and reports from the BIO's online publication archive.[1] I recorded my findings in the form of notes (58 pages) and annotated document images (60 pages). These notes and images emphasized details of interactions between organizations, particularly between the PROs and private companies.

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[1] For the BIO publication archive, visit http://www.bio.gc.ca/info/publications-eng.php (accessed August 2013).

Appendix C

Expert Interview Screenshots

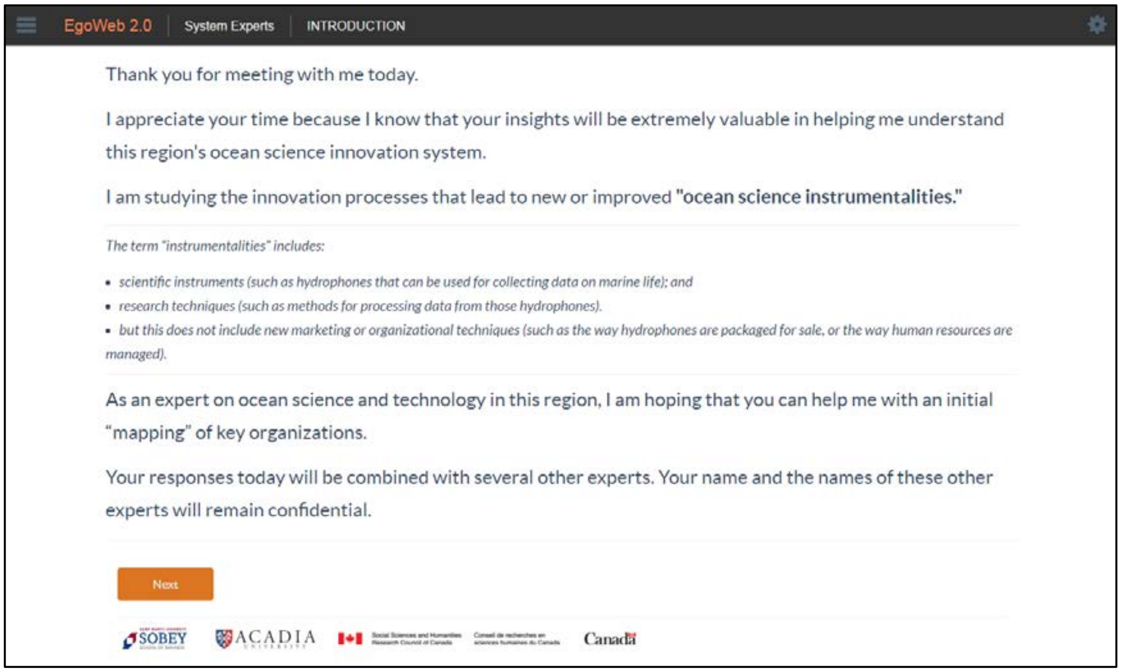


Figure C1. System experts interview — screen 1.

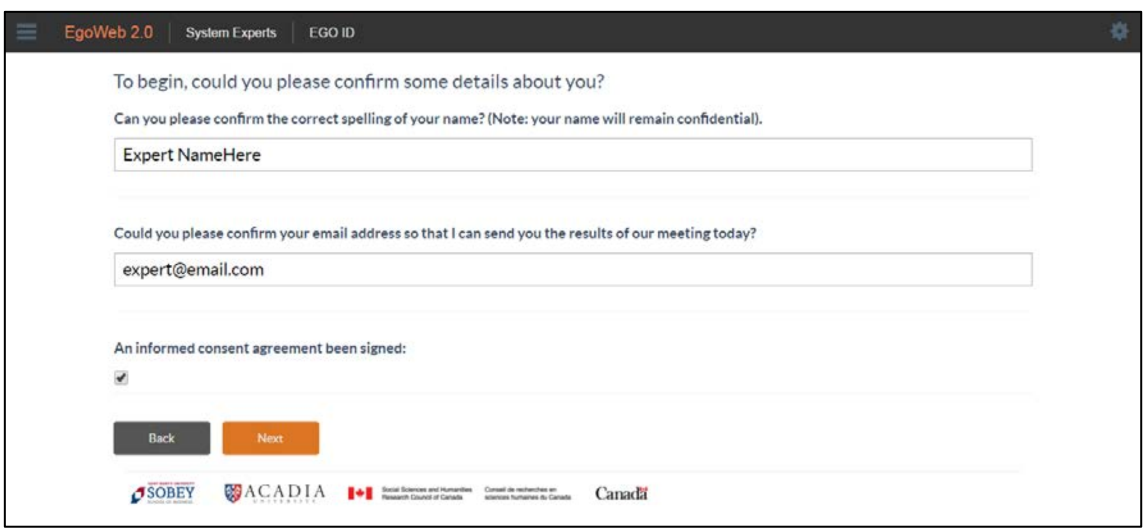


Figure C2. System experts interview — screen 2.

Figure C3. System experts interview — screen 3.

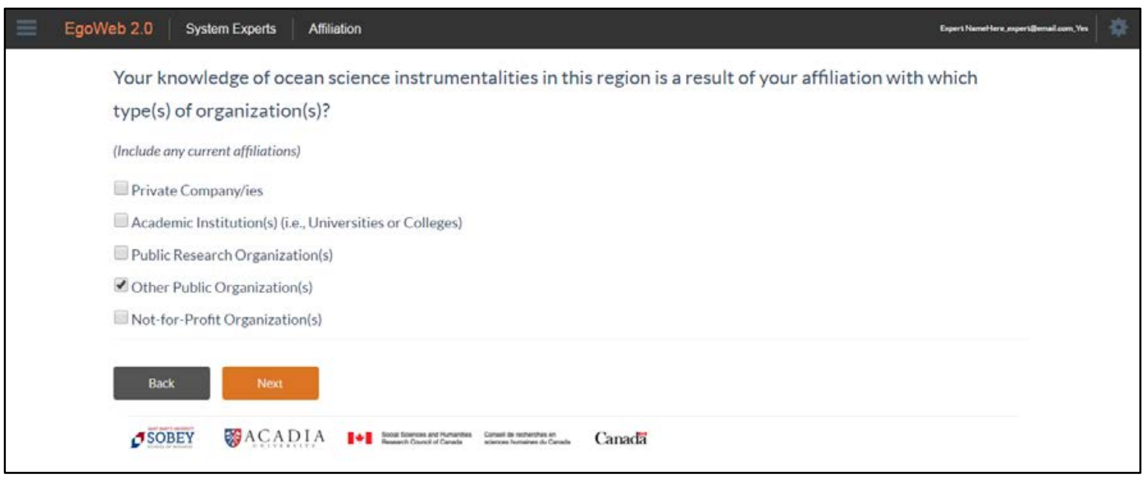


Figure C4. System experts interview — screen 4.

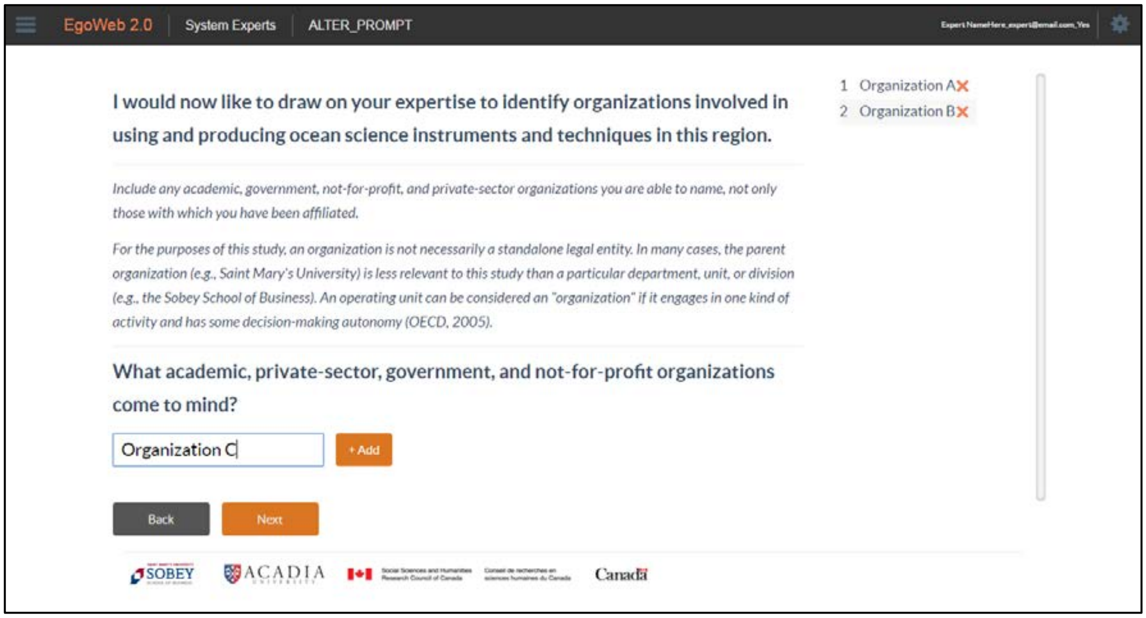


Figure C5. System experts interview — screen 5.

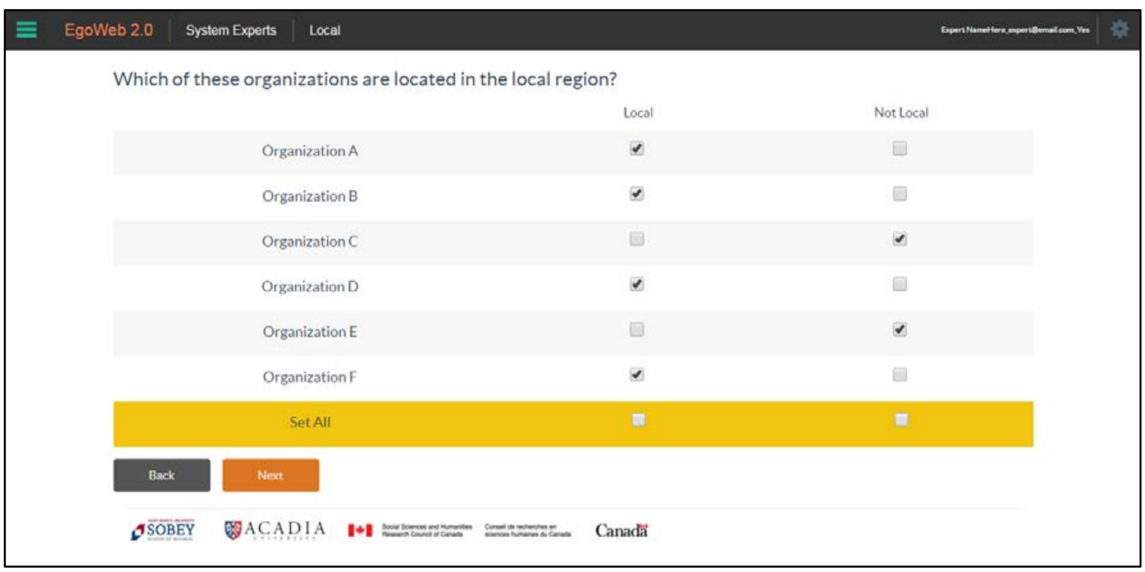


Figure C6. System experts interview — screen 6.

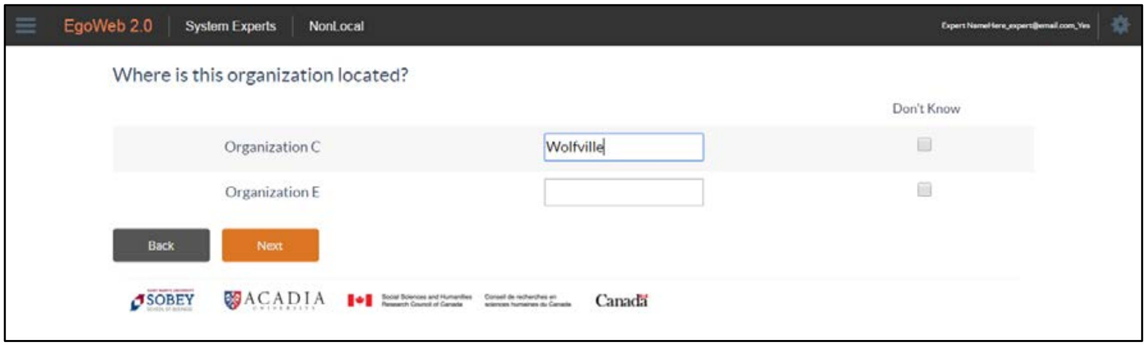


Figure C7. System experts interview — screen 7.

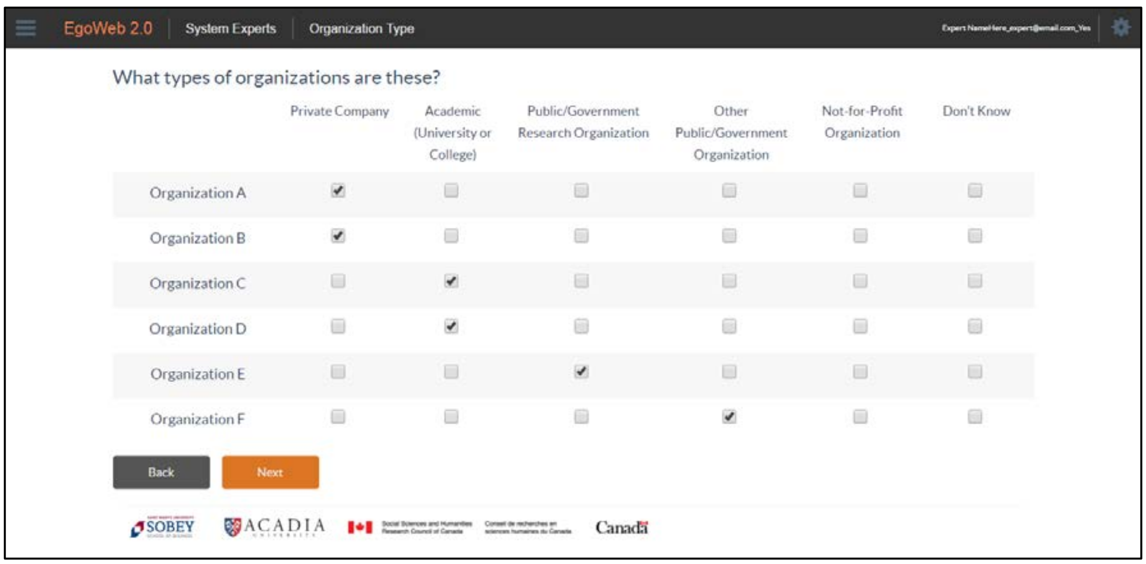


Figure C8. System experts interview — screen 8.

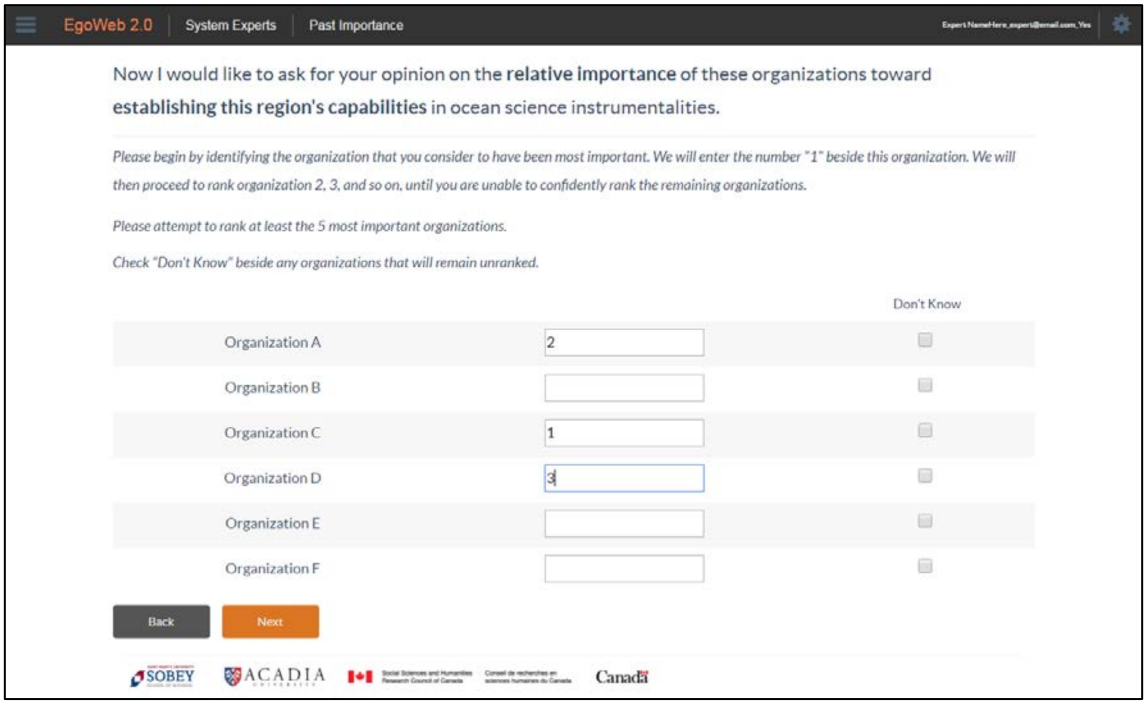


Figure C9. System experts interview — screen 9.

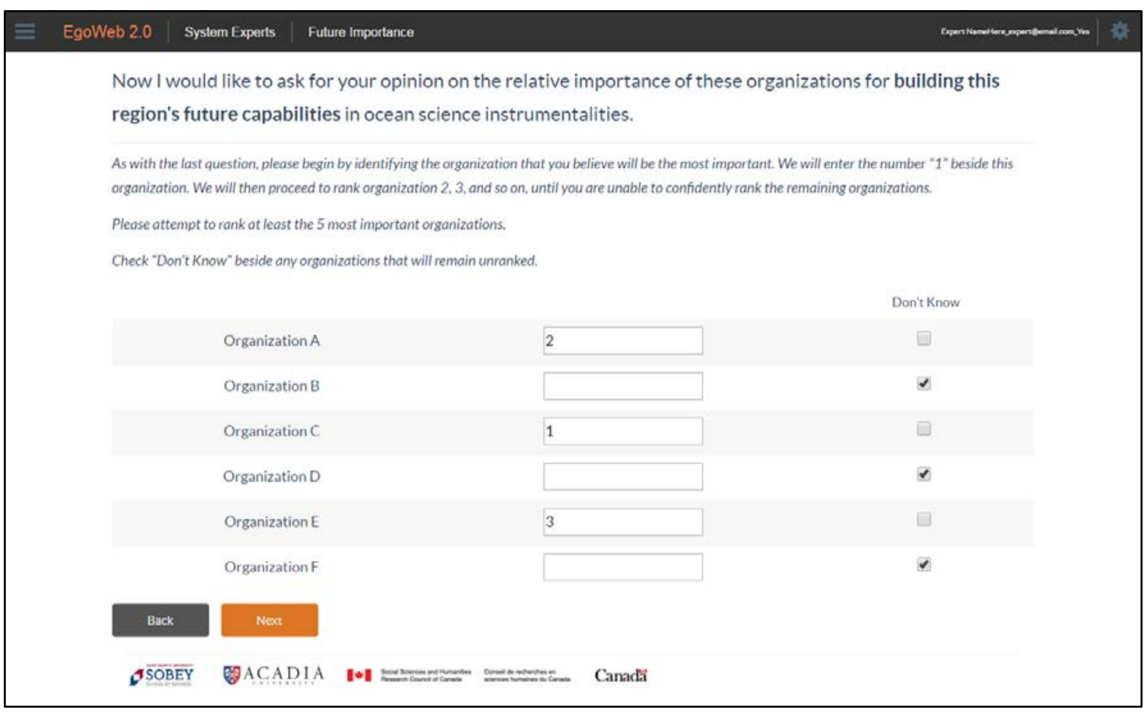


Figure C10. System experts interview — screen 10.

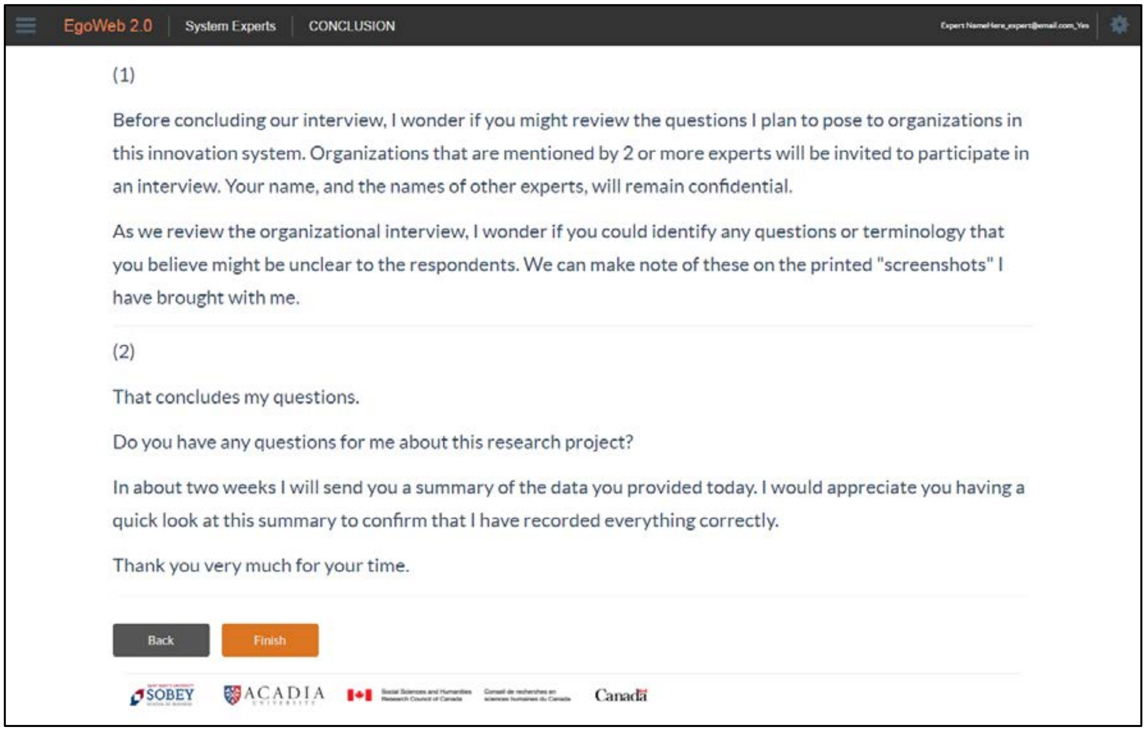


Figure C11. System experts interview — screen 11.

Appendix D

Organizational Key Informant Interview Screenshots

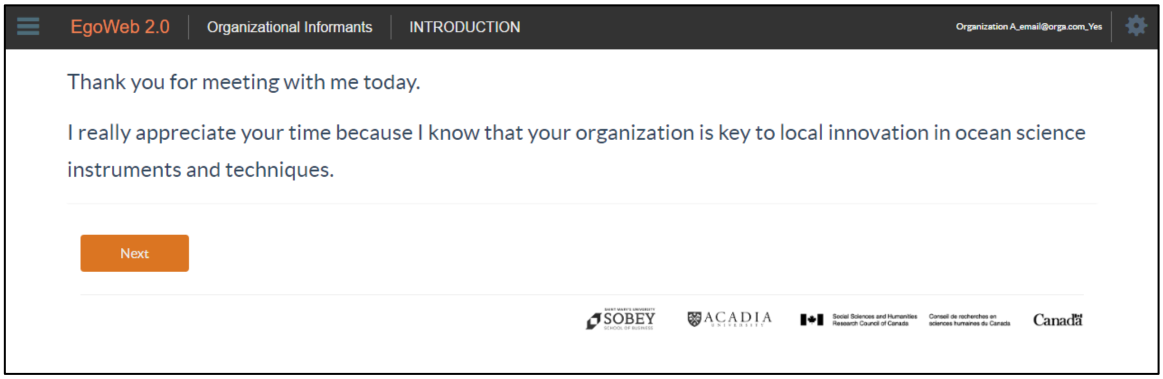


Figure D1. Organizational key informants interview — screen 1.

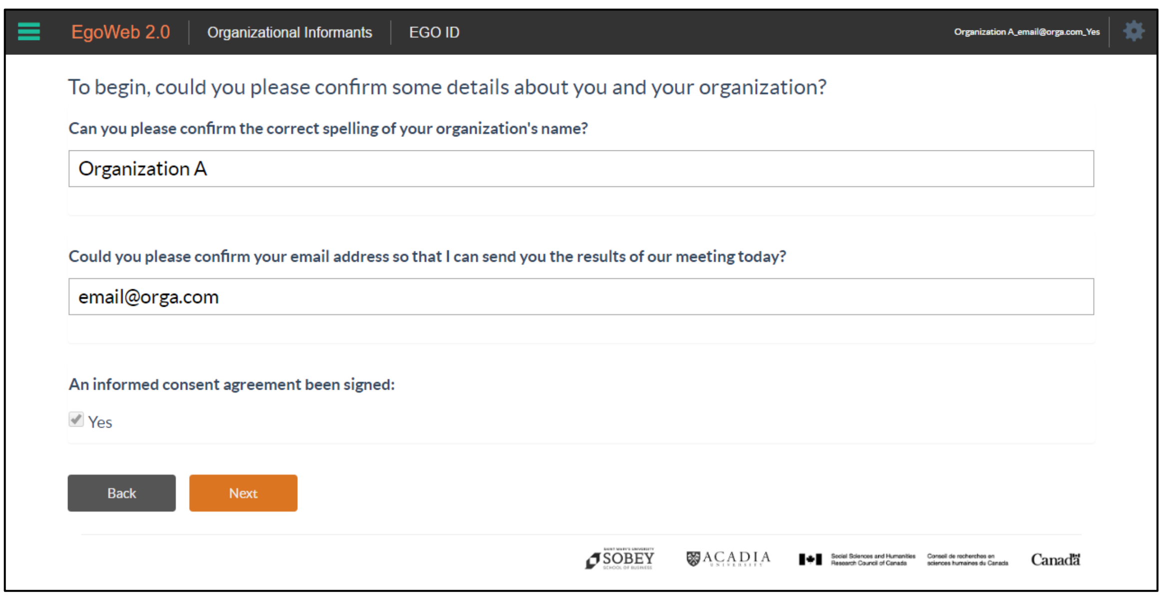


Figure D2. Organizational key informants interview — screen 2.

Figure D3. Organizational key informants interview — screen 3.

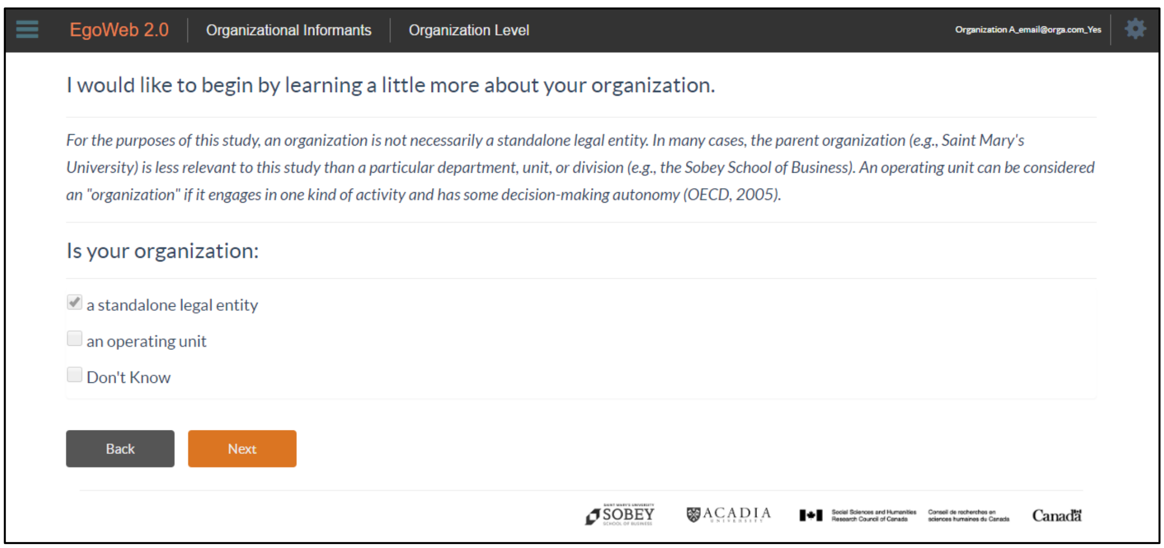


Figure D4. Organizational key informants interview — screen 4.

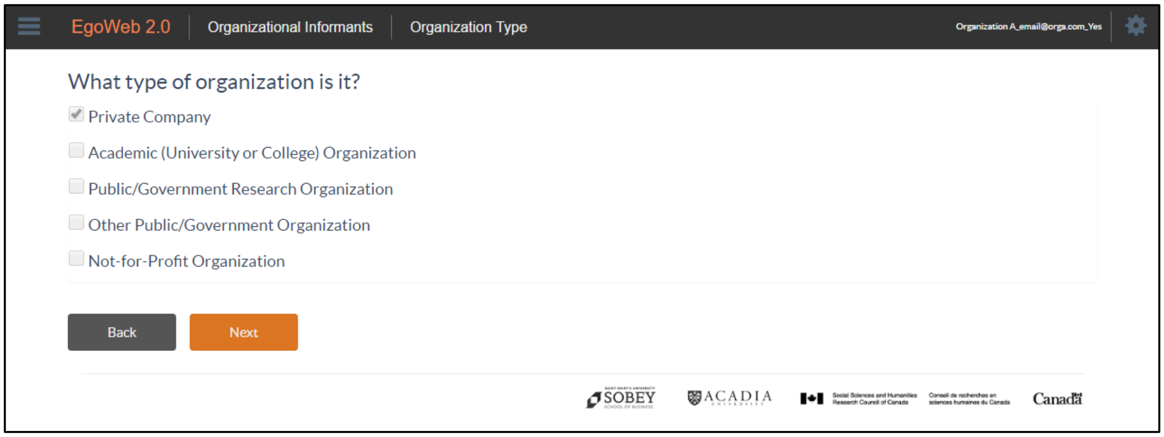


Figure D5. Organizational key informants interview — screen 5.

Figure D6. Organizational key informants interview — screen 6.

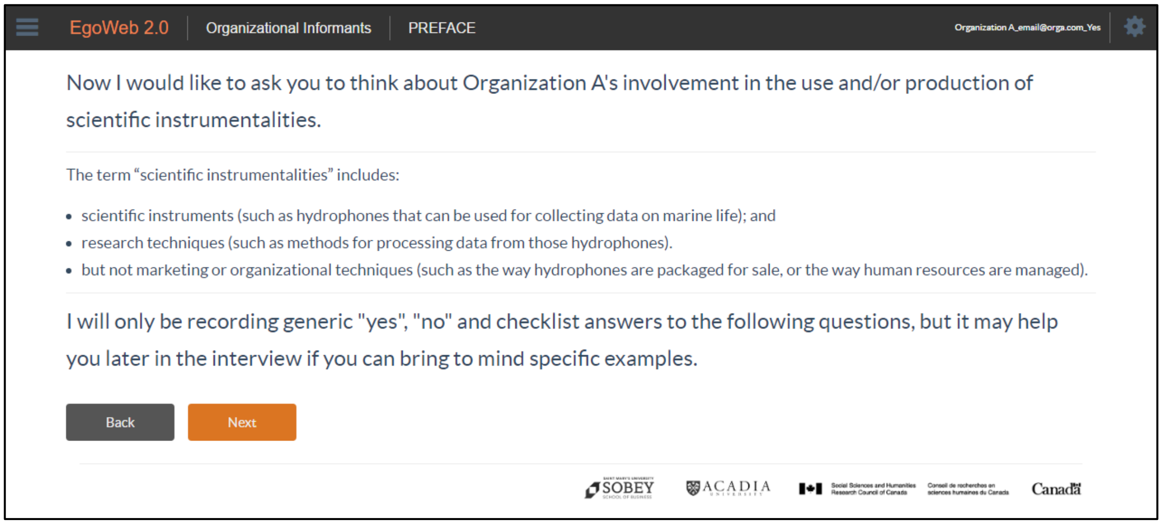


Figure D7. Organizational key informants interview — screen 7.

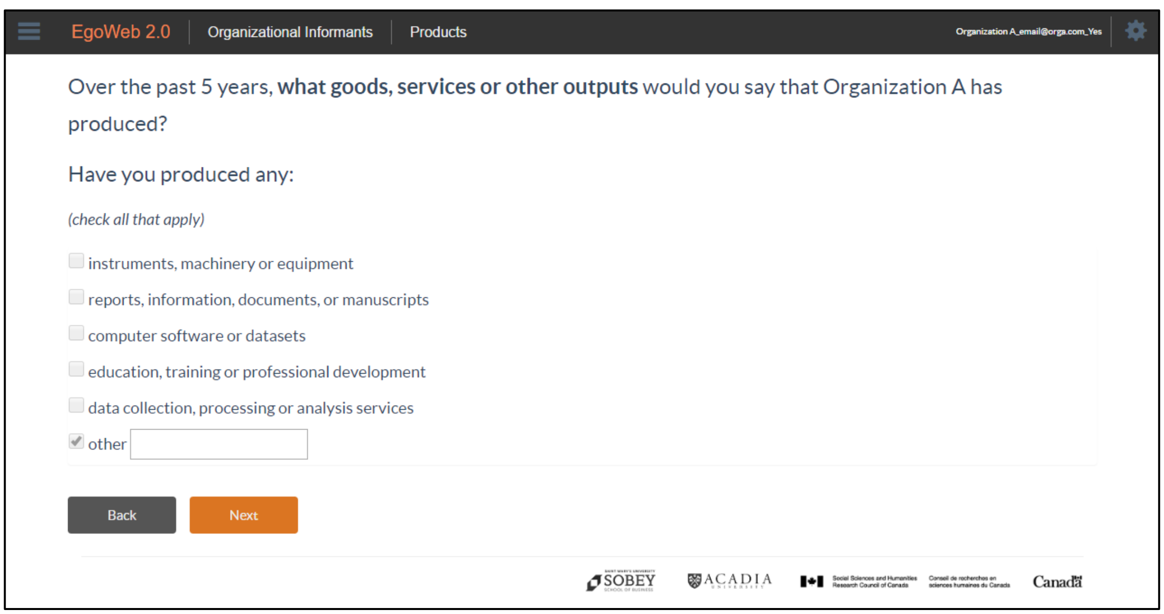


Figure D8. Organizational key informants interview — screen 8.

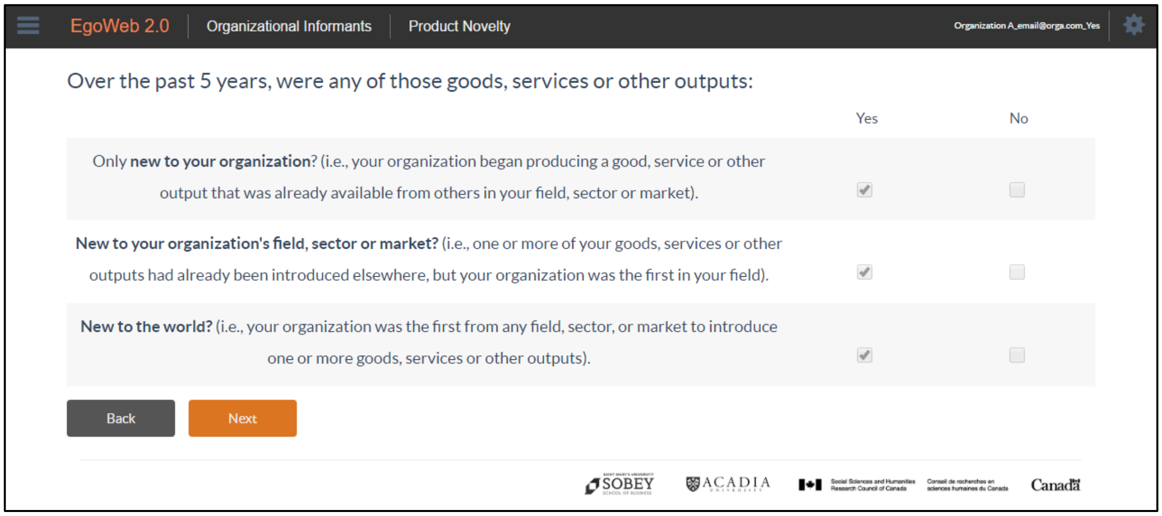


Figure D9. Organizational key informants interview — screen 9.

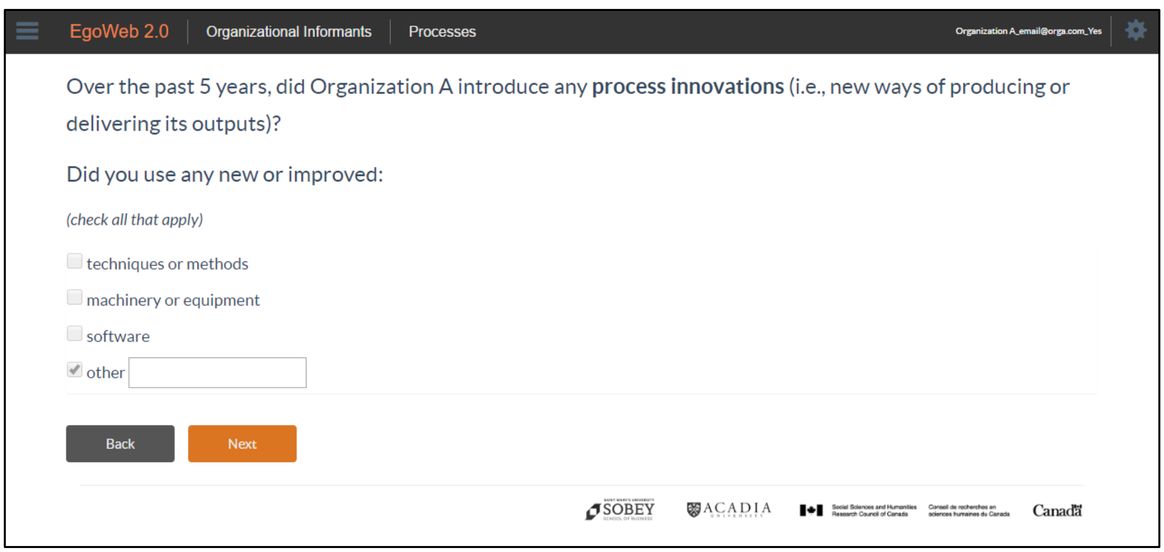


Figure D10. Organizational key informants interview — screen 10.

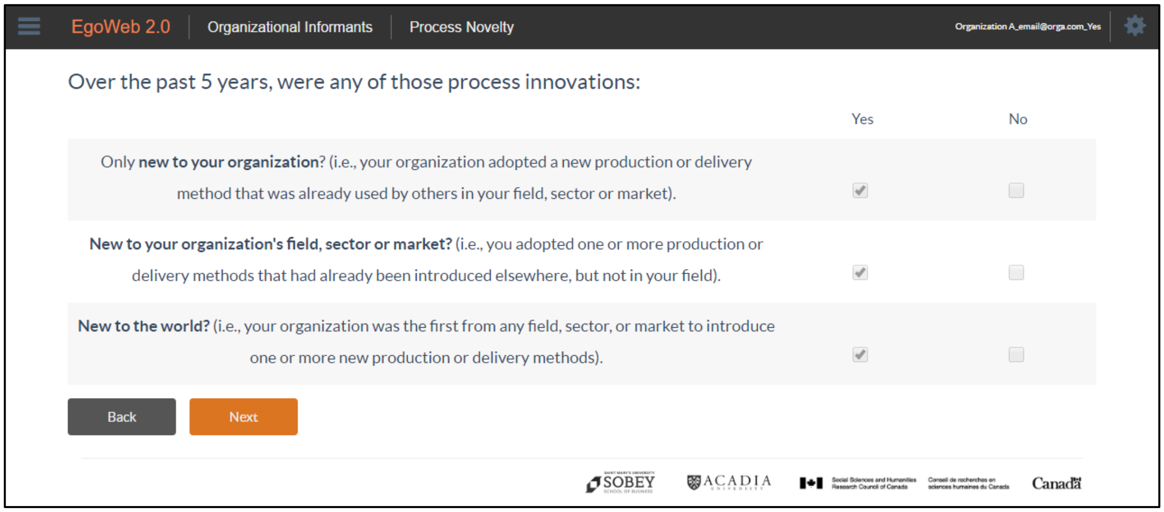


Figure D11. Organizational key informants interview — screen 11.

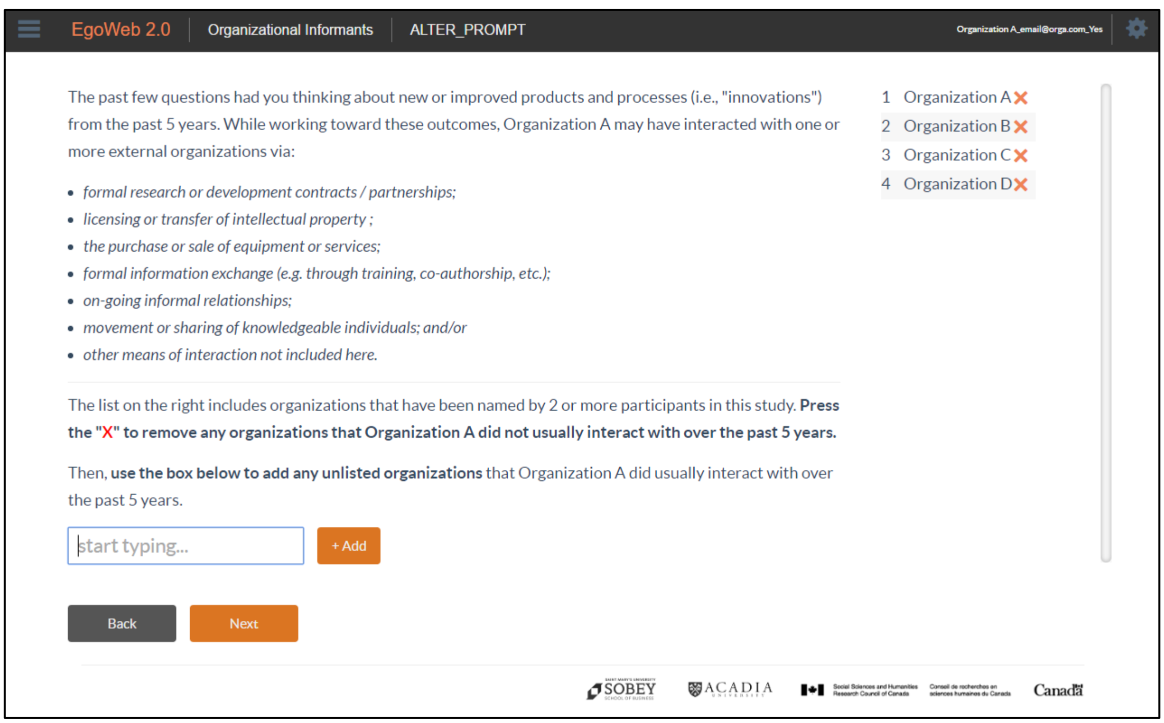


Figure D12. Organizational key informants interview — screen 12.

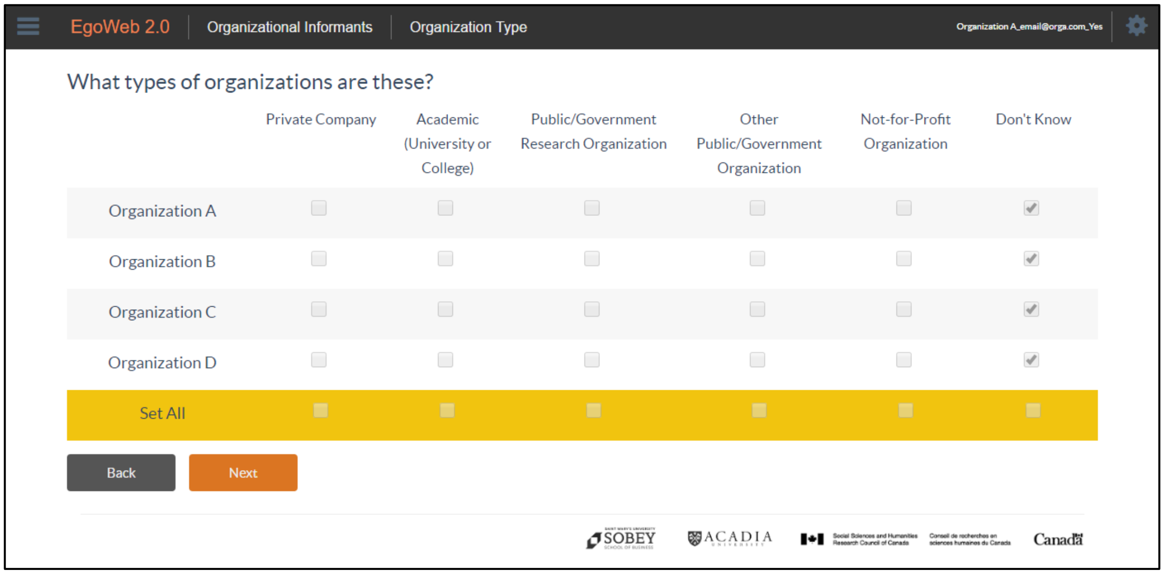


Figure D13. Organizational key informants interview — screen 13.

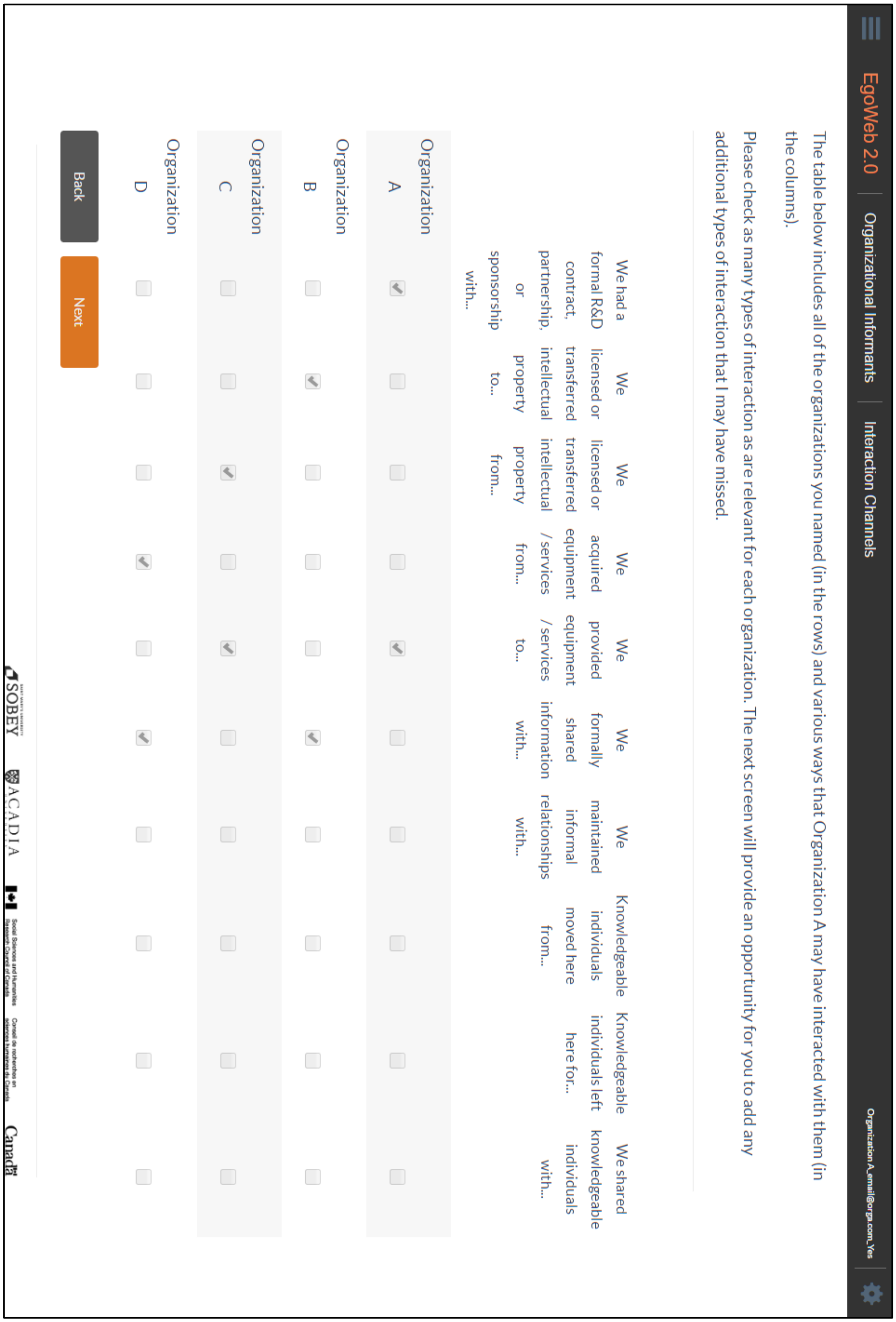


Figure D14. Organizational key informants interview — screen 14.

Figure D15. Organizational key informants interview — screen 15.

Figure D16. Organizational key informants interview — screen 16.

Appendix E

Informed Consent Agreement 1 – System-Level Experts

SYSTEM EXPERTS

OCEAN SCIENCE INSTRUMENTALITIES

INFORMED CONSENT AGREEMENT

Project Title: Innovation in Ocean Science Instrumentalities on Canada's Atlantic Coast.

SMU REB: File #16-534
ACADIA REB: File #16-34

Ryan T. MacNeil[1,2]
Principal Investigator

Claudia De Fuentes
Supervisor

[1]PhD Candidate
Sobey School of Business
Saint Mary's University
923 Robie Street,
Halifax, NS B3H 3C3

Ryan.MacNeil1@smu.ca
(902) 472-2597

[2]Lecturer
Manning School of Business
Acadia University
24 University Avenue
Wolfville, NS B4P 2R6

Ryan.MacNeil@acadiau.ca
(902) 585-1652

Assistant Professor
Sobey School of Business
Saint Mary's University
923 Robie Street,
Halifax, NS B3H 3C3

Claudia.DeFuentes@smu.ca
(902) 420-5851

INTRODUCTION

Hello. My name is Ryan MacNeil. I am a PhD candidate at Saint Mary's University and a member of the business faculty at Acadia University. As part of my doctoral studies, I am conducting research under the supervision of Dr. Claudia De Fuentes at Saint Mary's. My PhD studies have been funded through a Joseph Armand Bombardier Doctoral Scholarship from the Social Sciences and Humanities Research Council of Canada.

You are being invited to take part in my study on ocean science innovations in this region.

PURPOSE OF THIS RESEARCH

This region has long been recognized as a world-leader in ocean science and technology. Our present-day ocean technology industry emerged from work at a number of university and government laboratories. However, most studies of innovation downplay the innovation activities of publicly-funded organizations and focus only on innovation in private industry. This research aims to understand the interactions between many different types of public, private, and not-for-profit organizations.

I will be using network analysis to map out interactions between organizations in this region that use and/or produce ocean science instruments and techniques. I am particularly interested in identifying key organizations in the system, key types of interactions between organizations, and the robustness of this innovation system in the face of change (e.g., what might happen if we lose key organizations?). This research presents no real or potential conflicts of interest for me, my supervisor, my universities, or SSHRC (the funding body).

OCEAN SCIENCE INSTRUMENTALITIES INFORMED CONSENT 1 – 2

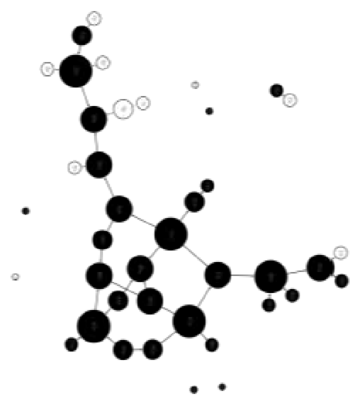
WHO IS BEING INVITED TO PARTICIPATE?

You are being invited to participate because of your position as a particularly well-informed observer of this innovation system. You are under no obligation to participate, but are eligible to do so if you feel that you are able to name the most important local organizations that have been using and/or producing ocean science instrumentalities (i.e., instruments and/or techniques) over the past 5 years.

WHAT DOES PARTICIPATING MEAN?

If you choose to participate, you will be asked to complete an in-person interview. During the interview, you will be asked to (1) name organizations that are currently involved in using and producing ocean science instruments and techniques, (2) tell me whether they are local (or where else they are located in this region), (3) label these organizations by type (i.e., academic, government research, other government, private company, not-for-profit), and (4) rank the relative importance of these organizations in the past and for the future. At the end of the interview I will also ask you to (5) briefly review the questions that I plan to ask each organization and identify any questions or terminology that you believe might be unclear to them. The interview is expected to take approximately 1 hour.

Your responses will be used to identify possible participants for this study. Organizations that are named by two or more experts (like you) will be added to a roster of possible participants. This roster will be presented to participants during each subsequent interview, but the roster will not be published with the research results.



Your responses will also be merged with data from other respondents to construct network maps like the one to the right. Note that the maps will only name public and not-for-profit organizations. Private companies will be represented by a common colour code or shape. In addition, network metrics will be calculated such as the relative importance of each organization within the network (e.g., the “degrees of separation” between one organization and all others). Confidentiality and privacy measures are detailed below.

WHAT ARE THE POTENTIAL BENEFITS OF THIS RESEARCH?

Although there are no direct benefits to you as a participant, you may benefit indirectly from the opportunity to reflect on this innovation system. The local ocean science and technology community could benefit from a greater understanding of its innovation system. There are potential broader benefits to science, and to society, through an improved understanding of innovation system dynamics. The research may also yield policy insights that could support the further development of ocean science instrumentalities in this region.

V1 (25-05-16)

WHAT ARE THE POTENTIAL RISKS FOR PARTICIPANTS?

Risks are minimal for involvement in this study. However, you may feel uneasy when asked to name and provide information about specific organizations. The names of private sector companies are being collected for snowball sampling and data matching purposes only. Participants in this study will be provided with a list of all those organizations that are mentioned by two or more experts (like you). This list will not be included in the research results. The details connecting individual respondents with the organizations they name will only be available to the principal investigator and his supervisor.

You may also be concerned about social risks related to a breach of confidentiality. All analyses will be conducted using a de-identified and coded dataset (i.e., no individual participants will be named and data on private sector companies will not be reported). Confidentiality and privacy measures are detailed below.

HOW CAN I WITHDRAW FROM THIS STUDY?

Participants are able to withdraw from the research study at any time before the results are compiled (August 31, 2016), without prejudice to pre-existing entitlements. If any new information becomes available that is relevant to your decision to continue or withdraw from participation, you will be notified in a timely manner. To have your data removed from the study, simply send an email request to Ryan.MacNeil1@smu.ca.

WHAT WILL BE DONE WITH MY INFORMATION?

The names of individual interviewees will remain confidential at all times. All data obtained from private sector companies will be kept confidential and will only be reported in an aggregate format (by reporting only combined statistics and by representing all private companies using one common colour/shape on network diagrams). No one other than the primary investigator and supervisor listed above will have access to the data about individual interviewees and the data about private companies. Data about public and not-for-profit organizations will be treated as public-record (i.e., not confidential), except where relationships with private sector companies are noted. To protect the strategic interests of private companies, this data will remain confidential.

During the interview, data will be collected using a touch-screen computer. The data will be immediately stored in a password protected and encrypted database on this computer. After the interview, you will receive a copy of the data to verify accuracy.

Your data will be linked with data from other respondents in a relational database. In this database, the names of private companies will be replaced with nondescript alpha-numeric codes. Your name will be replaced with a pseudonym (i.e., Expert #1). The de-identified data set will be stored on separate media from the coding key. Both files will be encrypted. The dataset will be stored in the primary investigator's office (at Acadia University) and the coding key will be stored in the supervisor's office (at Saint Mary's University) along with copies of all informed consent agreements.

No individual participants will be identifiable in the research results. When the results of this study are presented, individual private sector organizations will not be identified. Public and not-for-profit organizations will be identified using their proper names. All data will be securely destroyed five years after it has been collected.

HOW CAN I GET MORE INFORMATION?

You are invited to contact the researcher or his supervisor at the email addresses or phone numbers at the top of this form. Information about the results of this study will be posted on the primary investigator's website when they become available: www.ryanmacneil.com. If you have an adverse reaction (e.g., experience distress) stemming from participation in this study, please contact the researcher.

CERTIFICATION

This research has been reviewed and approved by the Saint Mary's University Research Ethics Board (REB# 15-534). If you have any questions or concerns about ethical matters, you may contact the Chair of the Saint Mary's University Research Ethics Board at ethics@smu.ca or 1-902-420-5728.

This research has also been reviewed and approved by the Acadia University Research Ethics Board (REB# 15-34). If you have any questions or concerns about ethical matters, you may contact the Chair of the Acadia University Research Ethics Board at smaitzen@acadiau.ca or 1-902-585-1407.

PARTICIPANT'S AGREEMENT

I understand what this study is about and appreciate the risks and benefits. I have had adequate time to think about this and have had the opportunity to ask questions. I understand that my participation is voluntary and that I can end my participation at any time. By consenting, I have not waived any rights to legal recourse in the event of research-related harm.

__________________________________ ________________
SIGNATURE OF PARTICIPANT DATE

____
PRINT NAME OF PARTICIPANT

RESEARCHER'S AGREEMENT

I agree to conduct the study in accordance with the constraints imposed by this document.

____
RYAN T. MACNEIL

Appendix F

Informed Consent Agreement 1 – Organizational Key Informants

ORGANIZATIONAL INFORMANTS

OCEAN SCIENCE INSTRUMENTALITIES

INFORMED CONSENT AGREEMENT

Project Title: Innovation in Ocean Science Instrumentalities on Canada's Atlantic Coast.

SMU REB: File #16-534
ACADIA REB: File #16-34

Ryan T. MacNeil[1,2]
Principal Investigator

Claudia De Fuentes
Supervisor

[1]PhD Candidate
Sobey School of Business
Saint Mary's University
923 Robie Street,
Halifax, NS B3H 3C3

Ryan.MacNeil1@smu.ca
(902) 472-2597

[2]Lecturer
Manning School of Business
Acadia University
24 University Avenue
Wolfville, NS B4P 2R6

Ryan.MacNeil@acadiau.ca
(902) 585-1652

Assistant Professor
Sobey School of Business
Saint Mary's University
923 Robie Street,
Halifax, NS B3H 3C3

Claudia.DeFuentes@smu.ca
(902) 420-5851

INTRODUCTION

Hello. My name is Ryan MacNeil. I am a PhD candidate at Saint Mary's University and a member of the business faculty at Acadia University. As part of my doctoral studies, I am conducting research under the supervision of Dr. Claudia De Fuentes at Saint Mary's. My PhD studies have been funded through a Joseph Armand Bombardier Doctoral Scholarship from the Social Sciences and Humanities Research Council of Canada.

You are being invited to take part in my study on ocean science innovations in this region.

PURPOSE OF THIS RESEARCH

This region has long been recognized as a world-leader in ocean science and technology. Our present-day ocean technology industry emerged from work at a number of university and government laboratories. However, most studies of innovation downplay the innovation activities of publicly-funded organizations and focus only on innovation in private industry. This research aims to understand the interactions between many different types of public, private and not-for-profit organizations.

I will be using network analysis to map out interactions between organizations in this region that use and/or produce ocean science instruments and techniques. I am particularly interested in identifying key organizations in the system, key types of interactions between organizations, and the robustness of this innovation system in the face of change (e.g., what might happen if we lose key organizations?). This research presents no real or potential conflicts of interest for me, my supervisor, my universities, or SSHRC (the funding body).

OCEAN SCIENCE INSTRUMENTALITIES INFORMED CONSENT 2 – 2

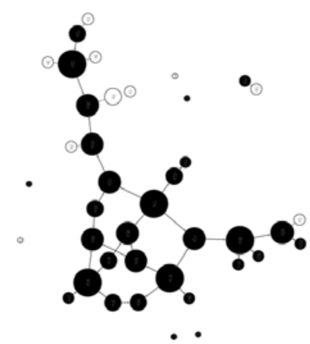
WHO IS BEING INVITED TO PARTICIPATE?

You are being invited to participate because your organization was identified as an important oceanographic innovator by either (a) one or more experts I consulted; or (b) another participant in the study. You are under no obligation to participate, but are eligible to do so if your organization (1) interacted with external organizations in some way, (2) for the purposes of using or producing ocean science instruments or techniques, (3) in the past 5 years.

WHAT DOES PARTICIPATING MEAN?

If you choose to participate, you will be asked to complete an interview either in-person or using Skype. The interview includes 7 components. During the interview, you will be asked about (1) what type of organization this is; (2) the number of employees working at this organization (overall, and those specifically in research & development), (3) the kinds of outputs this organization has produced over the past 5 years (and the novelty of those outputs), and (4) whether there have been any changes to the way these outputs are produced (and the novelty of those changes).

You will then be asked to (5) identify the external organizations that your organization interacted with from a pre-set list. You will be asked to add additional names to your list as necessary. From among all of the organization you identify, you will be asked to (6) label them by type (i.e., academic, government research, other government, private company, not-for-profit), and (7) identify the ways that your organization has interacted with them (e.g., formal partnerships, IP transfer, informal knowledge sharing). The interview is expected to take approximately 1 hour.



Your responses will be merged with data from other respondents to construct network maps like the one to the right. The list of organizations we discuss will not be published. Public and not-for-profit organizations will be named, but private companies will be represented by a common colour code or shape. Network metrics will be calculated such as the relative importance of each organization within the innovation network (e.g., the "degrees of separation" between one organization and all others). Confidentiality and privacy measures are detailed below.

WHAT ARE THE POTENTIAL BENEFITS OF THIS RESEARCH?

You will receive a network map illustrating your organization's innovation network. This map will be drawn using the data collected from your interview (you will not have access to data collected from any other organization). This may help your organization to understand its external innovation network.

You may also benefit indirectly from participating in this study. The local ocean science and technology community could benefit from a greater understanding of its innovation system. There are potential broader benefits to science, and to society, through an improved understanding of innovation system dynamics. The research may also yield policy insights that could support the further development of ocean science instrumentalities in this region.

WHAT ARE THE POTENTIAL RISKS FOR PARTICIPANTS?

Risks are minimal for involvement in this study. However, you may feel uneasy when asked to name and provide information about your organization's strategic collaborators. The names of private sector companies are being collected for snowball sampling and data matching purposes only. Participants (like you) will be provided with a list of all organizations that were mentioned by two or more experts. This list will not be included in the research results. All additional data provided from and about private sector companies will be kept confidential.

You may also be concerned about social or strategic business risks related to a breach of confidentiality. All analyses will be conducted using a de-identified and coded dataset (i.e., no individual participants will be named and data on private sector companies will not be reported). Confidentiality and privacy measures are detailed below.

HOW CAN I WITHDRAW FROM THIS STUDY?

Participants are able to withdraw from the research study at any time before the results are compiled (September 30, 2017), without prejudice to pre-existing entitlements. If any new information becomes available that is relevant to your decision to continue or withdraw from participation, you will be notified in a timely manner. To have your data removed from the study, simply send an email request to Ryan.MacNeil1@smu.ca.

WHAT WILL BE DONE WITH MY INFORMATION?

The names of individual interviewees will remain confidential at all times. All data obtained from private sector companies will be kept confidential and will only be reported in an aggregate format (by reporting only combined statistics and by representing all private companies using one common colour/shape on network diagrams). No one other than the primary investigator and supervisor listed above will have access to the data about individual interviewees and the data about private companies. Data about public and not-for-profit organizations will be treated as public-record (i.e., not confidential), except where relationships with private sector companies are noted. To protect the strategic interests of private companies, this data will remain confidential.

During the interview, data will be collected using a touch-screen computer (or in a live "screen sharing" window for Skype interviews). The data will be immediately stored in a password protected and encrypted database on this computer. After the interview, you will receive a copy of the data to verify accuracy.

If any of your organization's collaborators also participate in the study, your data will be linked with theirs in a relational database. In this database, the names of individuals and private companies will be replaced with nondescript alpha-numeric codes. The de-identified data set will be stored on separate media from the coding key. Both files will be encrypted. The dataset will be stored in the primary

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investigator's office (Acadia University) and the coding key will be stored in the supervisor's office (Saint Mary's University) along with copies of all informed consent agreements.

No individual participants will be identifiable in the research results. When the results of this study are presented, individual private sector organizations will not be identified. Public and not-for-profit organizations will be identified using their proper names. All data will be securely destroyed five years after it has been collected.

HOW CAN I GET MORE INFORMATION?

You are invited to contact the researcher or his supervisor at the email addresses or phone numbers at the top of this form. Information about the results of this study will be posted on the primary investigator's website when they become available: www.ryanmacneil.com. If you have an adverse reaction (e.g., experience distress) stemming from participation in this study, please contact the researcher.

CERTIFICATION

This research has been reviewed and approved by the Saint Mary's University Research Ethics Board (REB# 16-534). If you have any questions or concerns about ethical matters, you may contact the Chair of the Saint Mary's University Research Ethics Board at ethics@smu.ca or 1-902-420-5728.

This research has also been reviewed and approved by the Acadia University Research Ethics Board (REB# 16-34). If you have any questions or concerns about ethical matters, you may contact the Chair of the Acadia University Research Ethics Board at smaitzen@acadiau.ca or 1-902-585-1407.

PARTICIPANT'S AGREEMENT

I understand what this study is about and appreciate the risks and benefits. I have had adequate time to think about this and have had the opportunity to ask questions. I understand that my participation is voluntary and that I can end my participation at any time. I am in a position to participate in this research on behalf of my organization. By consenting, I have not waived any rights to legal recourse in the event of research-related harm.

SIGNATURE OF PARTICIPANT

DATE

PRINT NAME OF PARTICIPANT

PARTICIPATING ON BEHALF OF

PRINT NAME OF ORGANIZATION

RESEARCHER'S AGREEMENT

I agree to conduct the study in accordance with the constraints imposed by this document.

RYAN T. MACNEIL

V3 (08-05-17)