Researching the Researcher:

A Social Network Analysis

of the

Multidisciplinary Knowledge Creation Process

By

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Author's Declaration for Electronic Submission of a Thesis

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

This research describes the relationship between several social network characteristics and knowledge creation outputs in the form of patented intellectual property of researchers by investigating the case of the University of Waterloo. Based on a literature review in the domains of social networks and knowledge creation, this research focuses on the position of knowledge creation between social closure theory and structural hole theory. These are the two seminal theories of the creation of social capital through social networks. From this body of literature, this thesis develops the research question involving five hypotheses. These hypotheses test whether network density, strength of relationships, diversity of relationships, and amount of research funding have a positive correlation with the number of patents held by the researcher, and whether network size has a negative correlation with number of patents held by a researcher. The data for this research comes from a variety of secondary sources including the University's Office of Research, UWDIR online directory, NSERC research awards search engine, and CIPO patent database. Using a combination of social network analysis and statistical regression analysis, this research shows that network density, diversity of relationships, and amount of research funding have a positive correlation with knowledge creation outputs, while network size has a negative relationship with knowledge creation outputs. Understanding the relationship that these social network factors have with the knowledge creation outputs can help the University develop strategies to help improve their knowledge creation processes, thereby putting the University in a stronger position to facilitate the

development of patentable ideas and innovations by encouraging the development of research centres and institutes that intersect disciplinary boundaries.

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1 Introduction

The opening section of the introductory chapter to this thesis presents the motivation for this research. This is followed by a brief introduction to the key topic and concepts, how this research fits into the extant literature, and an overview of the research question. The final sections in this chapter give a brief outline of methods and results of this study.

1.1 Motivation for Research

In today's technological age, innovation and knowledge creation are key factors in the development of new advances in technology. These advances are important both to the economy and to society as a whole. New products and processes are constantly being improved upon, becoming faster, more efficient, and of higher quality. This not only helps in reducing costs and increasing sales for businesses, but also helps improve the quality of life for society as well. Although these new advancements in technology sometimes occur within the context of the research and development departments of private sector corporations, this type of innovation and knowledge creation also occurs because of the research conducted at Universities as well. Universities have a strong research focus and face pressures from both government and private sector industry to produce patentable intellectual property that can be licensed or otherwise commercialized. Innovative discoveries often occur at the intersection of disciplinary boundaries.

Universities use organizational structures such as research centres and institutes to help researchers transcend disciplinary boundaries and provide an administrative structure to support multidisciplinary research. The research of faculty members in these institutes and centres at the Universities often leads to new ideas and designs that result in entrepreneurial initiatives such as start up companies as well as licensing and patenting of these innovations.

The nature of knowledge creation and innovation is complex. This research looks at some of the social aspects of how research is conducted in a University environment. Researchers observe that their group of peers, which include other faculty researchers, have an influence on their own ability to develop new ideas for my research. Not only do these peers contribute through their existing knowledge, but simply sharing ideas with them also helps create a synergy of knowledge. The advice of other researchers can be extremely useful, especially when they have some previous experience or expertise in relevant areas of research. In addition, brainstorming and getting feedback from peers who have divergent areas of research also provides an opportunity to develop new ideas through a more diverse spectrum of perspectives. The influence of these peers, who are part of a researcher's social network, is the inspiration for this research to explore the social aspects of research and knowledge creation at the University.

This research is important as it brings together relevant ideas from two domains of research, social networks and knowledge creation, adding to the understanding of the research process at the University. The discussion of the relevant domains of extant literature and the results of this study serve to illustrate the importance of research centres and institutes as organizational structures within the University that facilitate

interdisciplinary collaboration and knowledge creation. The innovative discoveries of researchers in these centres and institutes contribute to the potential for patentable intellectual property.

The following sections in this chapter introduce the concepts on social networks and knowledge creation in the context of the University of Waterloo as a case study. The subsequent chapters on Theory Development and Methodology provide more background into the existing theories in these domains, develop the arguments and framework for this research, as well as detail the approach and design of this study.

1.2 Extant Literature

To understand the nature of knowledge creation in the context of a University research environment, there are two domains of existing research that are relevant in this discussion. These bodies of extant research comprise the theoretical framework for the research presented in this thesis. This section introduces the concepts of social networks and knowledge creation presented in the following chapter on Theory Development.

The first body of extant research pertains to social network theory, also referred to as network sociology. It examines the various benefits of social capital that arise from different social network structures. The two seminal theories in this domain are Burt's (1992) structural hole theory and Coleman's (1990, 1988) social closure theory. Both theories propose that social capital is a product of the relationships between people in social networks; however, each theory takes an opposite argument on which social

network characteristics are involved in the creation of social capital. Burt's structural hole theory proposes that sparsely connected networks are the source of social capital, whereas Coleman's social closure theory proposes that highly cohesive networks generate social capital. Burt (2000) argues however, that both social processes described by each of these two theores are necessary. In recent studies, researchers attempt to resolve the differing, yet complementary, aspects of these two theories. Johanson (2001) proposes a balance of social capital that involves both the instrumental approach and expressive approach to the creation of social capital, while Birley and Nicolaou (2003) present a similar contingency approach to social capital that proposes that arguments of both Burt's structural hole theory and Coleman's social closure theory are valid, however each is applicable under different contingencies.

Although the relevance of network sociology is observable in a variety of applications from behavioural science to venture capital, social networks also play an important role in the innovation and the knowledge creation process (Brown and Duguid, 2000; Chiffoleau, 2005; Carre et al., 1989). There is existing research on the types of network characteristics that may influence the knowledge creation process by network sociology pioneers such as Burt (1992) and Coleman (1998, 1990) as well as more recent studies by Cannella and McFadyen (2004), Birley and Nicolaou (2003), and Drejer and Jorgensen (2005).

The second body of extant research that this study explores relates to theories of knowledge creation. Marr (2004) discusses three different models of knowledge creation in organizations. Ayvary and Jyrama (2005) and Nielsen (2004) show that collaboration and alliances between researchers generate a synergy of knowledge that is greater than

the knowledge that can be created by each researcher independently. This study also discusses the importance of research centres in the University and the role they play in facilitating the formation of social networks through opportunities for collaboration and encouraging new research and knowledge creation.

Membership and participation in research centres, which serve as communities of practice, result in the formation of social structures among the individual researchers within the University. In general, a community of practice is a social group that facilitates research. For the purposes of this research, the concept of a community of practice is used in the same context as social networks. This study describes these social structures and uses the bodies of extant literature to develop a theoretical framework to explain the relationship of these characteristics with the knowledge creation productivity of the University.

1.3 Positioning of Research

The research presented in this thesis builds on the domains of extant research pertaining to knowledge creation and network sociology by developing a theoretical framework at the intersection of these domains, and is an application of social network theory in the context of knowledge creation. The case study of the University of Waterloo provides a good example of an organization that has a strong focus on knowledge creation as one of its primary organizational outputs and that demonstrates self-organizing, research oriented social networks in the form of research centres and institutes. There are

currently over 40 different research groups, centres, and institutes listed by the University's Office of Research. These research centres and institutes help facilitate interdisciplinary collaboration and the formation of social networks of faculty members with similar research interests.

The type of cooperative collaboration exhibited at the University demonstrates certain characteristics consistent with Coleman's cohesive network theory based on the need for trust and reciprocal sharing of knowledge and research resources within the University research community. There are also elements of competitive and self-serving behaviour than any individual exhibits to some degree, such as efforts to maximize organizational resources allocated or budgeted in favour of an individual's own research, or competing for limited funding, which are consistent with Burt's structural hole theory of social capital. Johanson (2001) refers to Burt's structural hole theory and Coleman's social closure theory as the instrumental approach and expressive approach, respectively. The research presented in this thesis proposes that the contingency factors that exist in the University research environment allow for the presence of both social processes in the knowledge creation productivity of the University. On one hand, the organizational culture of the University research community is one of collaboration and cooperation is consistent with the expressive approach to social capital. On the other hand, the competitive behaviour of some researchers and the need to bridge disciplinary boundaries are aspects of the instrumental approach to social capital, both of which benefit the knowledge creation productivity of the University.

Knowledge is seen as a product of an individual person. However, the context in which an individual creates new knowledge often occurs within the construct of social

interactions as opposed to in isolation (von Krogh, Ichihjo and Nonaka, 2000; Avary and Jyrama, 2005; Marr, 2004). Collaborative relationships and alliances between individual researchers help create an environment conducive to the generation of new knowledge (Hall and Graham, 2004; Nielsen, 2004). Researchers such as Forman and Markus (2004), Drejer and Jorgensen (2005), and Hkupic et al. (2002), who have done related studies regarding knowledge creation and the role of collaboration, have identified the need for further research pertaining to social network characteristics relating to the creation of knowledge in a collaborative research environment. Forman and Markus specifically propose the use of network sociology as a tool for the analysis of knowledge creation in collaborative research environments in their recommendations for areas of future research.

Researchers in these respective domains of research, such as Drejer and Jorgensen (2005), and Hkupic et al. (2002), have observed the need for further research integrating these domains to explore the process of knowledge creation from a network sociology perspective. These researchers recognize that although collaboration and interdisciplinary research are often recommended, there is still a lack of empirical or theoretical research that validates the benefits of network sociology in the context of knowledge creation. Forman and Markus (2004) also recognize the value of applying social science theories, primarily network sociology models, to the study of collaborative interdisciplinary research and knowledge creation. They propose this link between the study of network sociology and knowledge creation as a recommendation for an area of further empirical quantitative exploration of their own existing qualitative research on this subject. The research presented in this thesis attempts to address the demand for

research that bridges the gap between these domains, as the importance of the intersection of these domains becomes increasingly evident.

The domain of research presented in this study is important because the University's relationship with industry depends in part on its knowledge creation productivity and the commercialization of this knowledge. The successful commercialization of the University's research and productive knowledge outputs play a role in both public sector and private sector industry funding, therefore understanding the nature of the University's knowledge creation process is important in maintaining its competitive advantage in terms of obtaining economic resources. By understanding which social network characteristics within the University's research community promote increased patenting productivity, the opportunity for the commercialization of this new knowledge also increases. This commercialization of knowledge can provide innovative new products and processes to private sector industry, which is a valuable commodity to these industries. Therefore, increasing performance of the University, in terms of its knowledge creation productivity, improves its competitive advantage in securing continued funding and investment from these private sector sources.

1.4 Overview of research question

This research describes the social structures created by faculty researchers and the social networks that form because of membership in multi-disciplinary research centres within the University of Waterloo. Although researchers' social networks are not limited their participation in research centres, this research focuses on the social networks defined by membership in research centers at the University. Research centres and institutes help facilitate interdisciplinary research at the University, and membership in them provides one mechanism to observe relationships and social structures among researchers. This thesis also examines the relationships that these social network characteristics have with the knowledge creation outputs in the form of patented intellectual property of the University's research community. The joint involvement in these research centres is one of the mechanisms within the University research environment that provides an opportunity for collaboration with other researchers, and the review of the extant literature shows that certain network characteristics encourage collaboration and that increased collaboration enhances performance in knowledge creation productivity. This research tests five hypotheses related to social network theory and the knowledge creation outputs of the University. The following chapters on Theory Development and Methodology explain the meanings of the constructs that these hypotheses describe. These chapters also detail the specific metrics used to measure these constructs.

1) Researchers who are members of denser networks have a greater propensity for patenting of intellectual capital.
2) Researchers who belong to large social networks have a lower propensity for patenting of intellectual capital.
3) Researchers with stronger relationships within their social networks have a greater propensity for patenting of intellectual capital.
4) Researchers with more diverse memberships in research centres and institutes have a greater propensity for patenting of intellectual capital.
5) Researchers with greater access to funding have a greater propensity for patenting of intellectual capital.

The purpose of this research is to examine the role that these social network characteristics have in the knowledge creation process in the University research environment. Understanding the nature of knowledge creation and the role that certain social network characteristics plays is of particular interest to Universities because one of their productive outputs is the generation of new knowledge. This research uses patents as a measure of the productive output of the knowledge creation process. Patenting of intellectual capital is only one measure of knowledge creation. Other forms of knowledge creation provide possibilities for future research as well. From an economics and managerial perspective, this knowledge creation is a vital component of the University's productivity and a source of its competitive advantage (Nonaka and Takeuchi, 1995; Drejer and Jorgensen, 2005). In the contexts of the University, this competitive advantage can be expressed in terms of proving its ability for knowledge

creation, attracting future researchers, securing research funding from both public and private sector, as well as maintaining its reputation as a leader in developing new technology and innovation. Although Universities are public institutions, they are increasingly finding a place in private sector industry, especially in the more highly innovative market segments (Drejer and Jorgensen, 2005; Hall et al., 2000; Mansfield, 1998; Etzkowits and Leydesdorff, 2000). The increased pressure to commercialize knowledge is evident in the Action File published by the AUCC in which University presidents have an agreement with the federal government to commit to tripling their commercialization performance while the government commits to increasing funding for research (AUCC, 2005).

1.5 Overview of Research Methods

The methods employed in this study consists of data collection from publicly accessible data sources, a network analysis of the social structure characteristics of the University's research community, and a statistical regression analysis that describes the relationship that these social network characteristics have with the knowledge creation outputs of the University.

The publicly accessible data sources that this study uses are secondary sources of data, since they do not involve the direct participation of the research subjects, who are the faculty members at the University, in obtaining the data for this study. These

secondary data sources include the University's Office of Research, UWDIR online directory, NSERC awards search engine, and CIPO patent database.

This study implements a social network analysis to obtain the social network characteristics of the University research community by processing the data from the University's Office of Research and UWDIR online directory using the UCINET social analysis software package. The next part of the methodology of this study combines this social network data with the NSERC research funding data and CIPO patent data for a statistical regression analysis. To perform the regression analysis, this study uses the SHAZAM statistical software application.

1.6 Summary of Results

The initial results of the research show statistically significant support for three of the five hypotheses. As proposed in the hypotheses, network size shows a negative relationship with the number of patents that a researcher produces, and the amount of research funding and diversity of research expertise that a faculty member has access to each show a positive relationship with the number of patents that a researcher produces. Although network density and the strength of association between researchers also showed a slight positive correlation with the number of patents produced, as proposed in the hypotheses, these two relationships are not statistically significant.

Upon review of the bivariate correlations between each of the five explanatory factors, the two factors that were not statistically significant in the original model,

network density and strength of association between actors, which are different measures relating to social closure, appear to be nearly collinear. Since each explanatory variable must be linearly independent, this study revises the regression model by removing the variable representing strength of association from the set of explanatory variables, since this variable had the lowest level of statistical significance. In the revised model involving the four remaining explanatory factors, each variable is statistically significant and demonstrates the predicted relationship as proposed by the respective hypotheses.

1.7 Implications of Findings

This research shows that certain characteristics of an individual researcher's social network exhibit a relationship with an individual's level of knowledge creation productivity, as measured by patented research. The implications of these findings on the University may be to develop ways of encouraging other researchers to develop similar social networks by changing the administrative structure of the research centres, by tailoring incentive programs to motivate these types of characteristics, or by changing the organizational culture of the University. The results of the revised model show that network density, diversity of relationships, and the amount of research funding have a positive correlation with knowledge creation outputs, and network size has a negative correlation with knowledge creation outputs. These findings have several organizational implications in terms of the University's research community. Since these explanatory factors seem to have a statistically significant relationship with the knowledge creation

outputs of the researchers, the University may want to encourage these characteristics among its research community. Research centres and institutes might limit membership to keep the groups more exclusive, while individual researchers may want to become members of a wider variety of different research groups in order to gain access to a broader set of research resources, and the University may develop ways to promote greater cohesion in research related social groups.

Because the social networks formed by membership in the various research centres and institutes at the University are self-organizing system due to the voluntary nature of participation in these communities of practice, strictly enforcing or imposing regulation on the research oriented social interactions of a researcher to conform to specified network characteristics would be unrealistic. Encouraging such social network characteristics among the member of its research community would require an approach that addresses changes to the organizational culture of the University. Developing strategies to promote these network characteristics as part of the University's organizational culture would be a topic for future research, which might fall under the domain of organizational design and behaviour. At this stage, it would require much more research into the development and implementation of such strategic actions on the part of the University, the research centres and institutes, and the individual faculty research members. These are, however, still useful ideas for further development in future research.

In addition to finding ways to encourage these types of social network characteristics among members of the University's research community, the results of this research may also be useful in identifying groups of researchers who already

demonstrate these characteristics and who may have a higher propensity for knowledge creation. Although the success of a researcher is not necessarily contingent on these social network characteristics, realizing that that these types of social network structures are conducive to the creation of new knowledge in the University research environment is still of value.

This research is a descriptive investigation of social network characteristics in the context of only one measure of knowledge creation, and only for the case of the University of Waterloo. Because of this, it is difficult to assert the general applicability of the findings of this research. However, the results of this research do confirm four out of the five hypotheses, and are supported by a strong framework of theory developed from the extant literature in the domains of social networks and knowledge creation. Therefore, this thesis should encourage future research into the relationship between social network characteristics and knowledge creation to help determine the generalizability of ideas presented in this research.

2 Theory Development

The theory development presented in this thesis constructs a model that describes the relationship between several important social network characteristics and the productive outputs of the University research process. The first few sections in this chapter explain the role of Universities in the economy in relation to achieving competitive advantage, and provide some background information on the University of Waterloo with respect to its knowledge creation activities and policy on intellectual property.

In order to understand the nature of these relationships, the first body of literature that following section in this chapter examines is the domain of social networks. In the discussion of social networks, this chapter discusses the two dominant competing theories of social capital creation in social networks as well as several approaches that attempt to resolve the conflicting arguments of these two theories. The next sections focus the discussion on theories on knowledge creation, how these theories relate to the benefit that arise from social networks, and identify commonalities at the intersection between these two domains. Finally, in this chapter, an evaluation of where the University research environment fits into the existing theory follows the sections on social networks and knowledge creation, and concludes with a summary of the hypotheses developed throughout this theoretical development chapter. The two main domains of research that this chapter focuses on are knowledge creation and social networks. These are appropriate bodies of literature to examine for the development of the framework of theory for this research; they address the types of social network positions and characteristics that are consistent with the performance of researchers in terms of their

propensity for a higher level of knowledge creation outputs in the form of patented intellectual capital.

2.1 Competitive Advantage

Although the research in this thesis deals with the interactions of individuals within the University environment, looking at interactions of the University itself with private sector industry at an organizational level helps illustrate the importance of knowledge creation to the competitive advantage of the University. In an economy-driven environment, even academic institutions must strive to maintain their competitive advantage in order to survive. Within the context of the University environment, competitive advantage includes the University's ability to prove its capacity for knowledge creation, attracting new researchers, securing funding for research, as well as upholding its reputation as a leading institution in research and innovation. Knowledge, and the effective management of knowledge, is an important source of competitive advantage, especially in turbulent business environments (Nonaka and Takeuchi, 1995; Hlupic, Pouloudi, Rzevski, 2002; Grant, 1996; Nielsen, 2004). Although the focus of this research does not directly examine the competitive advantage of Universities in terms of their ability to create new knowledge, it is still important to acknowledge the role of knowledge creation to the success of a University's competitive advantage since knowledge is one of its main productive outputs. The focus of the thesis is the influence of the social networks formed by co-membership in institutes on the patenting activity of individual faculty. This is

important, as patenting is one measure, although a highly specialized and conservative one, of new knowledge creation. Further, there is an increasing emphasis on creating patentable intellectual property because of pressure from government and other players for Universities to be more clearly seen as part of the national innovation and commercialization process.

Innovation shows a close link to scientific process, and accordingly the emergence of a tightly knit relationship between science, technology and economic performance has been observed over the last decade. Drejer and Jorgensen (2005) show that economic growth has an increasing connection with the generation and application of new knowledge. This supports the position that knowledge creation in the University environment is an important element in the continued economic viability of such academic institutions, especially as they continue to capitalize on commercialization of the research that develops within these institutions.

Debresson et al. (1998) examine the role of Universities as part of their study on the innovative activities of manufacturing industries in ten OECD (Organisation for Economic Co-operation and Development) countries, using data from the 1993 European Union Community Innovation Survey. In their study, one of the questions asked was about the significance of Universities in the innovation processes of organizations in the private sector. Although Universities were not identified as crucial, their data showed that 25 percent and 5 percent of the industry did identify Universities as being either moderately significant or very significant, respectively (Drejer and Jorgensen, 2005). The data shows that 15 percent of the innovating firms report collaboration with a domestic University or public research institute, and 5 percent report having collaborated

with foreign Universities or public research institutes. Although the representation of Universities constitutes a relatively low minority in the collaborations of innovative firms, they do still have a role in the knowledge creation and innovation process. This role is especially significant in certain types of research projects involving new science (Hall et al., 2000). Firms that engage in this type of involvement with Universities do so based on the premise that the more theoretical and practical research conducted at Universities would be of greater value in providing research insights that can anticipate future research problems in addition to aiding in current issues faced by the innovative firms. This illustrates one aspect of University involvement in private sector industry.

Mansfield (1998) provides further evidence to support the role of University collaborations in private sector innovative firms as he estimates that 15 percent of the new products developed in the period from 1986 to 1994 could not have been developed (at least not without substantial delay) in the absence of recent academic research. He also estimates that 8% of the new products were developed with substantial aid from recent academic research. His findings present a strong indication that the existence of a pubic R&D system, including academic institutions such as Universities, influences the innovative performance of an economic system.

Etzkowits and Leydesdorff (2000) propose the Triple Helix approach to innovation, which asserts the place that Universities have in corporate innovation. This approach focuses on the "network overlay of communications and expectations that reshape the institutional arrangements among Universities, industries, and government agencies" (Etzkowitz and Leydesdorff, 2000). Etzkowits and Leydesdorff (2000) coined the term Triple Helix to represent the three sources of innovation, which include

Universities, private sector industries, and government agencies, and the dynamic nature of the linkages between these three elements that all fit together in a non-predetermined organic fashion that from the conceptual Triple Helix structure. This is analogous to the double helix structure that connects the fundamental building blocks of life found in DNA. Their conceptual model of the Triple Helix approach also supports the importance that Universities have in the innovative developments in industry, and therefore asserts the importance of commercialization of knowledge creation outputs of the University to maintain its competitive advantage.

One of the observable successes of University research being transformed into industrial applications can be seen in the form of organizational emergence and entrepreneurial initiatives resulting from new research conducted at the University. Birley and Nicolaou (2003) refer to this type of entrepreneurial initiative from Universities as the 'University spinout phenomenon' in their study of social networks and University organizational emergence. In addition to the University spinout phenomenon (Birley and Nicolaou, 2003), other significant knowledge creation outputs that contribute to commercial success of Universities include patenting and licensing of research and products developed within the University (Jensen and Thursby, 2001; Agrawal and Henderson, 2002; Mowery et al., 2002; Thursby and Kemp, 2002; Birley and Nicolaou, 2003).

Public sector organizations such as Universities are facing increased rates of change because of the new demands for the commercialization of knowledge. Some of these changes manifest themselves in the form of an increased prevalence of University-industry co-operation, and increased reliance on external sources of funding, teamwork

and a concomitant need for inter-team learning (Gibbson et al., 1994; Ziman, 2000; Jacob, 2003; Hellstrom and Husted, 2004) in order to meet these new demands.

Having examined the importance of competitive advantage of Universities and the role that knowledge creation has in the continued maintenance of a University's success, the following sections present some background information on the University of Waterloo. The University is the subject of the case study presented in this research, as well as a description of the University's policy regarding intellectual property.

2.2 The University of Waterloo

This thesis presents a case study of the University of Waterloo, which has a reputation as a creative source of new technology and innovation. Maclean's gives the University of Waterloo top ranking in its overall ranking of comprehensive Universities as well as in all of the reputation categories in their survey, including #1 Highest Quality, #1 Leaders of Tomorrow, and #1 Most Innovative (Maclean's, 2005). Because of its reputation as one of the leading Universities in new technology research and innovation, the University of Waterloo provides a relevant example as the subject for this case study. In terms of knowledge creation and commercialization of this knowledge, the University of Waterloo has the potential to gain a competitive advantage by being a leader in conducting research in partnership with the private sector and transferring new knowledge and advances in technology to society. The University also operates its Technology Transfer and Licensing Office with the purpose of facilitating its researchers to commercialize the

products of their research in industry and private sector applications. The value that industry and the private sector have for the knowledge and research produced at the University is evident in the $103 million in research funding provided by both private and public sources in 2003 to 2004 alone (University of Waterloo, 2005). The University also holds 13 industry sponsored NSERC research chairs (University of Waterloo, 2005).

The research presented in this thesis uses the University of Waterloo as a case study, and investigates the individual researchers as the unit of analysis. As an indication of the commercializable knowledge creation outputs of the University, this study uses data regarding patented intellectual capital from Canadian Intellectual Property Office (CIPO).

The University of Waterloo is a strong promoter of collaborative research. It has established over 40 formal centres and institutes on campus, most with an interdisciplinary focus. In addition to internal collaboration within the University, Waterloo is also involved in interorganizational collaboration with an approximated 235 international linkage agreements, collaborative research activities, and education and research projects in 49 countries around the world (University of Waterloo, 2005). The research institutes and centres at the University serve as communities of practice, which provide the opportunity for researchers to collaborate with other researchers outside of the confines of the traditional disciplinary hierarchy. Co-membership in these research centres and institutes, which refers to researchers being members of the same research group, serves as an indicative mechanism to identify potential relationships between researchers. The social network analysis presented in this study uses these relationships to define the characteristics of the social networks.

2.3 UW Intellectual Property Policy

The University of Waterloo's policy on intellectual property (IP), Policy 73 (University of Waterloo, Secretariat, 2004), defines the meaning of intellectual property in the context of the University's academic community. It also describes the principles that the University follows in order to ensure that intellectual property rights are respected, both from a legal perspective, and in terms of the academic community's values. The legal perspective and academic community perspective on IP, however, each have a different emphasis in the importance of IP rights.

In legal terms, "IP is concerned with patents, copyrights, trademarks and the like, all of which provide legal protection for something that has real or potential commercial value", which has more of an emphasis on the word "property" and the issues regarding ownership of IP (University of Waterloo, Secretariat, 2004). From the academic community's perspective, although the legal considerations are still important, the primary emphasis is on the word "intellectual". To this end, the University "values openness, sharing of ideas, and scholarly activity, and its primary goals are to increase and disseminate knowledge" (University of Waterloo, Secretariat, 2004). The University's policy on IP also outlines the main principles to which members of the University's research community must adhere.

The first principle that Policy 73 describes is the ownership of intellectual property. In general, the University allows the creator to retain ownership rights of intellectual property created during the course of teaching and research related activities conducted at the University. There are, however, certain exceptions where the University

can retain ownership of IP rights. The second principle acknowledges that all contributors to works of IP should receive appropriate recognition for their contributions. The forms of recognition that this principle describes includes recognition of the creator, recognition through acknowledgement or citation, as well as recognition of the University in its capacity as nurturer, facilitator and/or supporter of scholarly work. The third principle states that all intellectual contributors are entitled to share in the proceeds in proportion to their contributions when there is the opportunity for commercial exploitation of IP created at the University. In the case of commercialization or other exploitive opportunities of IP, the fourth principle states that there must be discloser of this intention to the Vice-President, University Research or delegate. The final principle requires members of the University to respect the third-party IP rights of all other parties involved in the development of any works of IP at the University.

Section VII of Policy 73 describes the University's IP policy specifically pertaining to issues regarding patents. According to this policy, a patent is a document protecting the rights of the inventor(s) and a repository of useful technical information for the public (University of Waterloo, Secretariat, 2004). With regard to patents, two main parties benefit from the IP represented in a patent. The first is the creator or inventor in the form of legal rights and the potential commercializability of the product or process covered by the patent, and the second beneficiary is the general public in the form of new knowledge and technology that is disclosed. This form of benefit to both the individual as well as to the larger group is a consistent characteristic with the benefits of social capital in Coleman's social closure theory of social networks, which the following sections in this Theory Development chapter of this thesis discusses in further detail.

2.4 Social Networks

In this thesis, the faculty researchers at the University are the unit of analysis. Using the terminology of network sociology, each researcher is an *actor* or *node* in the network. When referring to a social network from a particular actor's frame of reference, that actor is referred to as the *ego*, and that social network is his or her *ego network*. In an ego network, any other actor connected to the ego is called an *alter*. The edges between nodes represent links or relationships between actors. These links can characterize any type of relationship between actors within a social network such as casual conversation, giving and receiving of advice, joint collaboration on a research project, or co-authorship of research publications. The frequency of interaction between actors defines the strength of the relationship (Wasserman and Faust, 1994). In the context of this thesis, these links represent co-membership in research centres at the University and the frequency of co-membership in the same research groups is a measure of the strength of the relationships between researchers. The networks examined in this study are internal to the University, and use co-membership in research centres and institutes as the means to determine associations within the network. Other methods for determining associations, such as co-authorship of research publications, asking and receiving of advice, and joint application of research grants is an area of future research. Social networks that extend beyond the University, such as associations with other academic institutions or private sector firms, are also a consideration for future research.

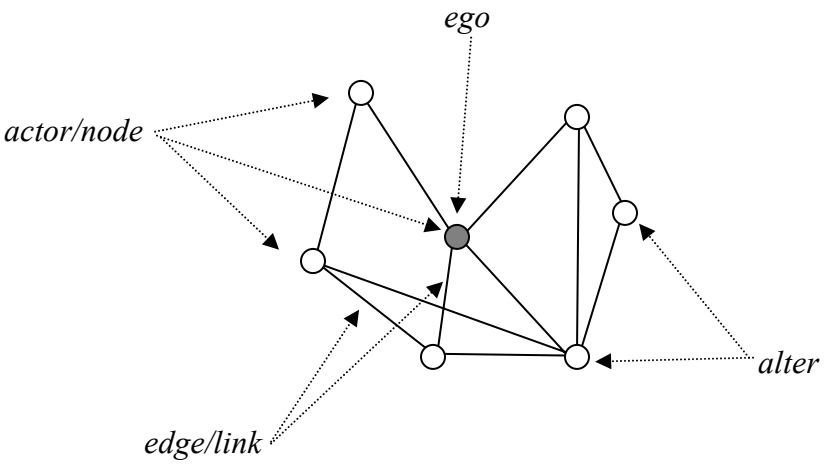


Figure 2-1: Example of ego network

Within the domain of social network research, there are two prevalent theories on how social capital develops within a social network. Social capital is a form of benefit, value, or asset that arises by virtue of social interaction, and is one of the productive outcomes of social networks (Gabby and Leenders, 2001). The two dominant theories explaining the role of social networks in the creation of social capital are Burt's (1992) structural hole theory, which argues for the benefits of sparse networks, and Coleman's (1990, 1998) social closure theory, which argues for the benefits of dense cohesive networks in the creation of social capital. A balanced contingency approach attempts to resolve the conflict between these two theories (Johanson, 2001; Birley and Nicolaou, 2003).

2.4.1 Social Capital

One of the key concepts in social network theory is the concept of social capital. Social capital is one of the productive outcomes of social networks (Gabby and Leenders, 2001). Although there is no single definitive definition of social capital (Burt, 2000, Gabby and Leenders, 2001), pioneering researchers in the domain of network sociology, such as Coleman (1990), Burt (1992), and Putnam (1993), have developed several leading definitions and theories of social capital. According to Coleman (1990, p.203), social capital is defined as "some aspect of social structure, facilitating certain actions in individuals who are within the structure". Similarly, Putnam (1995, p.67) defines social capital as "the features of social organization, such as networks, norms and social trust that facilitate coordination and cooperation for mutual benefit". Another definition proposed by Bourdieu (1997, p.49) states that "social capital is the sum of the resources, actual or virtual, that accrue to an individual or group by virtue of possessing a durable network of more or less institutionalized relationships of mutual acquaintance and recognition".

These definitions demonstrate several common attributes of social capital. The first attribute is the individual person or member, which is also referred to as an actor. The second attribute is the relationship between these actors, which can be characterized by any type of link or interaction between actors. The third common attribute is the network structure that forms because of the actors and the relationships that connect them to each other. Each of these definitions also describes an important feature of social

capital; the relationships and network formations amongst the individual actors create value to the members of these social structures.

There are also two proposed perspectives on the nature of the creation of social capital (Gabby and Leender, 2001); the first perspective views the creation of social capital as a natural or evolutionary process, and the second perspective views the creation of social capital as an intentional or purposeful process. The natural creation of social capital occurs due to the normal social interaction among individuals who may enter or leave these informal social networks. The second perspective of social capital creation, which is often of greater significance especially in the study of organizational dynamics and performance, proposes that individuals exhibit strategic behaviour by seeking out relationships and social networks to create social capital for their own benefit (Coleman, 1990; Burt, 1992; Gabby and Leender, 1999).

2.4.2 Structural Hole Theory

Although it is clear that social capital is a productive output of social networks (Gabby and Leenders, 2001) and there seems to be a relative level of consistency in the definitions of social capital, there are two apparently conflicting theories regarding how social networks generate social capital.

The first of these theories is Burt's (1992) structural hole theory, which is also referred to as the instrumental approach by Johanson (2001). Burt's (1992) argument for the benefits of sparse networks is based on the hypothesis that structural holes in the network act as bridges that connect people in the network to new information, knowledge,

and resources. The structural hole is a relationship of non-redundancy between two actors in a network (Burt, 1992). Since these actors are connected to each other by only one non-redundant path in the network, each of their respective resources can provide benefits to the other that are additive. When the relationship between actors is redundant, they are connected by multiple actors within the network, and can access the same resources via these multiple paths, therefore provide overlapping resource benefits.

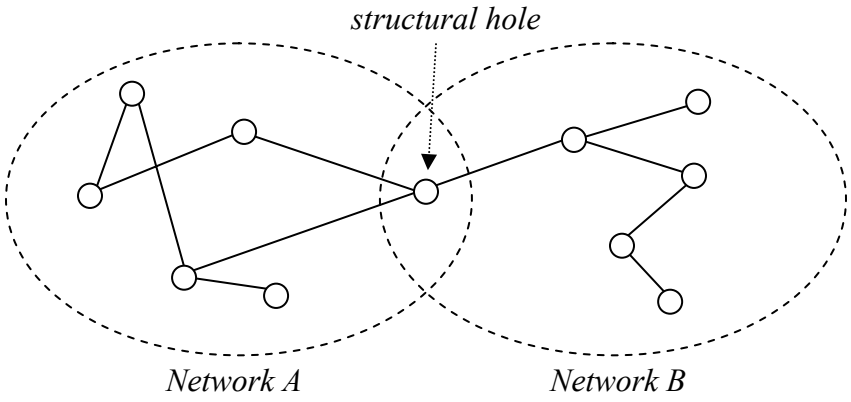


Figure 2-2: Example of sparse network

According to Burt (1992), sparsely connected networks are able to confer beneficial value because certain actors within the network serve as connecting bridges that provide access to non-redundant resources and information to other members of the network that would otherwise be inaccessible to these members, thereby giving these members the opportunity to gain control in a competitive environment. The actor that fills the position of a structural hole is the only point of contact between two otherwise disjoint networks, as shown in Figure 2-2, and is therefore in an advantageous position to

exploit the opportunities that these separate networks present in a competitive environment.

Sparsely connected social networks that exhibit structural holes can provide several distinct benefits. In addition to simply having access to non-redundant resources and information, Higgins (2001) shows that actors who have a greater number of non-redundant contacts in their network also have an increased opportunity and ability to change careers. Not only do structural holes present opportunities for lateral career advancement, but they also present opportunities for vertical career advancement. In highly competitive job markets, Burt (1992) finds that people belonging to sparse networks demonstrating high levels of non-redundancy lead to a faster rate of career promotion. These benefits are especially evident in environments that are more competitive.

2.4.3 Social Closure Theory

Coleman (1998, 1990) takes the converse argument, advocating the social closure theory, which Johanson (2001) refers to as the expressive approach to social capital. The social closure theory proposes that cohesive networks, which are densely connected networks as shown in Figure 2-3, can provide a greater value because the members are more tightly bound by a level of trust that leads to the assumption that members of the group will help each other by sharing knowledge and resources. The key elements of Coleman's social closure theory are trust, expectation, and reciprocal obligation.

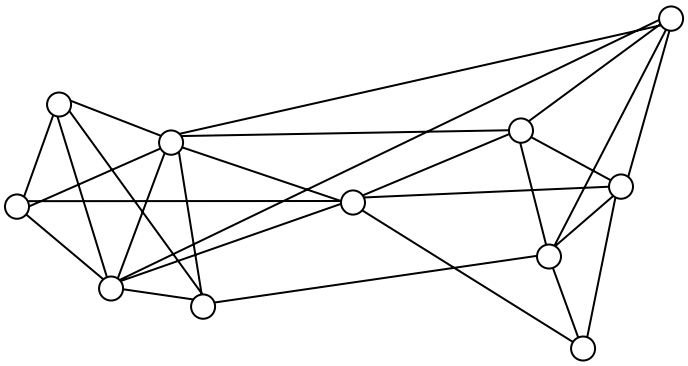


Figure 2-3: Example of dense network

Johanson's (2001) expressive approach identifies with the social closure theory by advocating that cohesive networks are able to foster trust and mutual obligation among members within a network (Coleman, 1988; Putnam, 1995). The value or benefit that social networks generate according to the social closure theory is associated with the number of reciprocal relationships that form between members in a network. As these reciprocal associations increase within the network, the network is able to provide greater social capital to its members.

The process that occurs between members within the network that generates social capital value is similar to the old axiom of the golden rule "do unto others, as you would have them do unto you". Consider an application of Coleman's social closure theory that relates to knowledge creation in the context of a research environment in the example of Bob and John who are both researchers at the same University. Bob is working on a research project; he asks John for some advice on a problem, and asks to use some of John's research facilities. John has some experience dealing with the type of problem that Bob is having and therefore has the knowledge to help Bob, and the

research that John is currently working on does not require the equipment that Bob is requesting the use of. John now faces the question of whether or not he should use his knowledge to help Bob and offer the use of his equipment. John has several options he could take.

1) He could simply volunteer his knowledge and resources for Bob to use.
2) He could charge a consulting fee to help Bob with his research problem and a rental fee for the use of his equipment.
3) Or, John could decide not to help Bob with his research problem and not let him use his equipment at all.

According to Coleman's social closure theory, if John decides on the third option not to help Bob, John would essentially be severing the network relationship with Bob and would not be able to incur any social capital benefits from this relationship in the future. If John chooses the second option to charge a consulting fee and rental fee to his fellow researcher Bob, the relationship would still be maintained to some degree, although Bob would have to pay these transaction costs associated his working relationship with John. Depending on the perceived fairness of these costs, Bob may be less inclined to seek future help from John or to help John if the tables were turned and John needed help from Bob. Assuming that Bob has the capacity to help John in the future, the most beneficial course of action for John to take, according to the expressive approach to social capital, is to volunteer his expert knowledge to help Bob with his research problem, and to offer Bob the use of his equipment since John is not using it

now anyway. Because there is no formal contractual agreement in this scenario, there is an implied level of trust between Bob and John. If John does something to help Bob, then John trusts that Bob will reciprocate sometime in the future. This trust establishes an expectation in John that Bob will reciprocate, and an obligation for Bob to meet this expectation by actually reciprocating at some point in the future. Bob now owes John something in return for helping him; the resulting relationship, based on trust, expectation, and obligation, is analogous to the concept of a credit slip held by John that Bob must eventually repay (Coleman, 1988). In a cohesive network, the cooperative actions of the individual members result in the creation of these credit slips and therefore generate anticipated benefits from membership within this social network (Johanson, 2001).

In Coleman's theory of social closure, social capital cannot be generated without trust, therefore trust in an integral component in the development of social capital. Nooteboom (2001) shows that trust among members of the network allows for expectation and obligation of reciprocal behaviour, which helps reduce transaction costs since the need for formal or legal contracts, monitoring and enforcing functions are reduced by the nature of the cohesive social network. Trust is not a commodity that can be purchased, and is not something that can be explicitly imposed upon people in any social environment, therefore achieving favourable network conditions conducive to trust is important towards creating social capital. Social norms and organizational culture help enable the cohesive network to impose and enforce the implicit rules of expectation, and obligation (Portes, 1998). Because of the sense of security that these social norms and culture provide in a cohesive social network, members of the network have less need to feel threatened or worried that other members will not reciprocate or contribute to the

community. This security allows trust to develop among members within the social community. If this trust were to be abused by a particular member, either by using network resources and not reciprocating, or by some other unethical behaviour that goes against the social norms of the cohesive network, then that individual would face the consequences and no longer be welcome to participate in that social network (Ferrary, 2002).

In addition to the economic benefits that cohesive networks can afford by virtue of reductions in transaction costs, cohesive networks also provide other important benefits. Pescosolido and Georgianna (1989) have shown that networks that are more cohesive provide greater social support mechanisms than non-integrated networks that lack strong social cohesion among its members. The presence of these social support mechanisms provides resources that help counteract the social and psychological stresses that arise in turbulent work environments (Lin and Ensel, 1989). In addition, individuals who receive greater social support from their network increase their propensity to generate radical innovation (Cummings, 1997; Monge and Contractor, 2000). These benefits not only provide significant value the individual members, but also the entire network as a whole.

2.4.4 Contingency Approach to Social Capital

Each of these theories on social capital seem to make logical sense when considered in isolation from each other, yet when both theories are considered together, an apparent dichotomy arises. Is social capital a product of structural holes in a sparsely connected

social network; or is it a product of social closure in a densely connected cohesive social network?

Birley and Nicolaou (2003) take a contingency approach to the role of social networks, which attempts to resolve the inconsistencies of two different sources of social capital. The first perspective on the role of social capital is presented by Burt (1992) who argues that sparsely connected networks are a significant precursor to competitive advantage, while the second perspective on the role of social capital presented by Coleman (1988, 1990) takes the opposite position, arguing that cohesive networks act as the precursor to competitive advantage. Johanson (2001) takes a similar approach to find a balance between Burt's structural hole theory and Coleman's social closure theory, which Johanson refers to as the instrumental approach and expressive approach, respectively. Table 2-1 outlines a comparison of the characteristics of these two prevailing theories of social capital creation.

Table 2-1: Comparison of instrumental and expressive approach to social capital

	Structural Hole Theory (Instrumental Approach)	**Social Closure Theory** (Expressive Approach)
Network	Sparse	Cohesive
Benefits	Instrumental	Expressive
Social Environment	Competitive	Cooperative
Scope of Analysis	Ego Networks	Ego/Total Networks
Beneficiary	Actor	Actor/Group

(Source: Johanson, 2001, p. 234)

Although these two theories of social capital creation seem contradictory in terms of the social network characteristics that each theory proposes as the source of social capital, the contingency approach argues that both theories are valid in their respective

ideas on social capital and are, in fact, complementary theories to each other. The validity of each argument, however, is dependent upon different contingencies (Burt, 1997; Gabbay and Zuckerman, 1998; Walker et al., 1997). Burt (2000) identifies five of these contingency factors that affect social capital creation: personality and culture, network content, number of peers and task uncertainty, network structure within and beyond groups, and borrowed social capital. Some of these factors play a role in determining which aspects of each theory of social networks are active in the University's research environment.

With network content as a contingency factor, Birley and Nicolaou (2003) show that business discussion networks benefit more from non-redundancy than social closure. In this type of network environment, the structural holes of the sparsely connected network give rise to benefits such as opportunity advancement, access to information and resources from seemingly disjoint sources, strategic timing of business transactions, and positive referrals to prospective new contacts.

Social support networks do not have the same benefits that arise for non-redundancy. This type of network benefits more from strong social cohesion within the network by providing greater mechanisms for social support (Pescosolido and Georgianna, 1989), which help to alleviate both social and psychological stress in turbulent organizational environments (Lin and Ensel, 1989). The level of trust also increases in social support type networks as the level of cohesion and strength of ties between members increases. These types of social support networks are evident among the University's research community.

In terms of personality and culture as a contingency factor (Burt, 2000), organizational cultures that support individualistic personalities that focus on individual performance tend to favour non-redundancy where as collectivistic cultures that are more team and group oriented tend to benefit more from social closure. The general organizational culture of the University is collectivistic, while at the same time there are also elements of individualistic personalities; this indicates that there is some balance between the need for personal achievement and organizational wellbeing, which is consistent with Johanson's (2001) approach to the balance of social capital between the two dominant social network theories.

The propensity to generate knowledge creation and radical innovation, which are forms of network content, also show a positive relation with denser cohesive networks that provide greater social support mechanisms as compared to sparse non-cohesive networks (Monge and Contractor, 2000; Cummings, 1997). This type of innovative network content demonstrated by the University is consistent with Coleman's social closure theory.

2.5 Knowledge Creation

Universities are organizations that have a strong focus on knowledge creation. The research that takes place within the University occurs within the context of a social community of peers, regardless if a researcher works independently or in collaboration with other researchers. Individual researchers maintain working relationships with other

researchers; these social interactions result in the formation of social networks that interconnect these researchers by making them members of a common research community.

The understanding of how new knowledge develops in these research communities depends on the model of knowledge creation adopted by a particular community. From a organizational epistemology perspective, there are three different models regarding knowledge and knowledge creation (Venzin et al., 1998, Marr et al., 2003a,b,c; Marr, 2004). Table 2-2 describes these three models.

Table 2-2: Models of knowledge creation in organizations

Epistemology	Description
Cognitivists	Congnitivists consider the identification, collection and central dissemination of information as the main knowledge development activity. Open organizations develop increasingly accurate pictures of their pre-defined worlds through the assimilation of new information. Knowledge is developed according to the universal rules; hence the context of the incoming information is important.
Connectionists	There are many similarities here to the congitivist viewpoint but a difference being that there are no universal rules. Rules are team-based and vary locally; therefore, organizations are seen as groups of self-organized networks dependent on communication. The connectionists believe that knowledge resides in the connections and hence focus on the self-organized dispersed information flow.
Autopoietics	Here the context of information inputs is unimportant as it is seen as data only. The organization is a system that is simultaneously open (to data) and closed (to information and knowledge). Information and knowledge cannot be transmitted easily since they require internal interpretation within the system according to the individual's rules. Thus, autopoietics develop individual knowledge, and respect that process in others.

(Source: Marr, 2004, p. 562)

Of these three models of knowledge creation, the epistemology most consistent with that of the University research community is the connectionist model. The team-based self-organizing networks proposed in the connectionist epistemology are evident in the research centre infrastructure at the University. Groups of researchers initiate the creation of these research centres, which are not part of the formal academic disciplinary hierarchy of the University. These self-organized groups facilitate connections between researchers with similar research interest or complementary areas of expertise and provide a cooperative mechanism for information flow and resource sharing.

The connectionist epistemology of knowledge creation adopted by the University research community is consistent with the expressive approach to social capital creation, which supports Coleman's social closure theory. The network content of these University research groups primarily focus on knowledge creation and innovation, which is a contingency factor that favours the social closure theory. The cooperative social environment exhibited by these research groups is also a feature more consistent with Coleman's social closure theory, as opposed to the competitive social environment proposed in Burt's structural hole theory. The knowledge created in these research groups is available to other members of the University and becomes a shared commodity that benefits not only the researcher responsible for this new knowledge, but also the University research community as a whole. The communal beneficiary aspect of newly created knowledge demonstrates another characteristic of social closure theory.

2.5.1 Creating Knowledge Through Relationships

The process of knowledge creation in the University research environment indeed relates to social networks, and demonstrates aspects that fit both with Coleman's social closure theory of social capital as well as with Burt's structural hole theory. The discussion thus far has been on the network as a whole; the following discussion goes one level deeper to describes how new knowledge develops between individual members within the network through their mutual relationship of collaboration.

Social networks provide opportunity for collaboration (Ayvary and Jyrama, 2005). Some of the observed benefits of collaboration include the ability to share and integrate different mental models and relate theories from different areas of expertise (Nonaka, Konno and Toyama, 2001; Avary and Jyrama, 2005; Marr, 2005). Collaboration also provides a mechanism for rapid feedback and capitalizes on existing knowledge of other researchers (Uzzi, 1996, Neilsen, 2005; Drejer and Jorgensen, 2005).

According to the organizational learning theory, knowledge is conducive to the formation of collaborative alliances, and the goal of such alliances is the acquisition, transfer, and absorption of complementary knowledge (Hill et al., 2000, Lyles and Salk, 1996, Nielsen, 2004). An alliance between two people creates a relationship between these two people; when more alliances are involved between more people, the relationships between these various actors result in the formation of a social network.

Each relationship that connects a particular pair of actors in the network has the potential to generate new knowledge. Neilsen (2004) develops a basic conceptual model that attempts to explain the role of relationships in the knowledge creation process. The

concept of knowledge embeddedness that Neilsen uses says that there is knowledge embedded in the relationships that exist within the network. This concept proposes a synergy of knowledge that arises from the sharing of knowledge among various actors that is greater than the sum of the knowledge of the individual actors. Therefore, the relationships between these actors within the network facilitate the creation of knowledge that would otherwise not be created. This theory of knowledge embeddedness is consistent with Coleman's social closure theory in the context of knowledge creation. Since knowledge is embedded in the relationships within the network, the greater the strength of these relationships and the more densely connected the network is, the greater the amount of knowledge that is embedded in the network. In a University research environment, this embedded knowledge is an asset both to the individual members of the network, and to the research community as a whole.

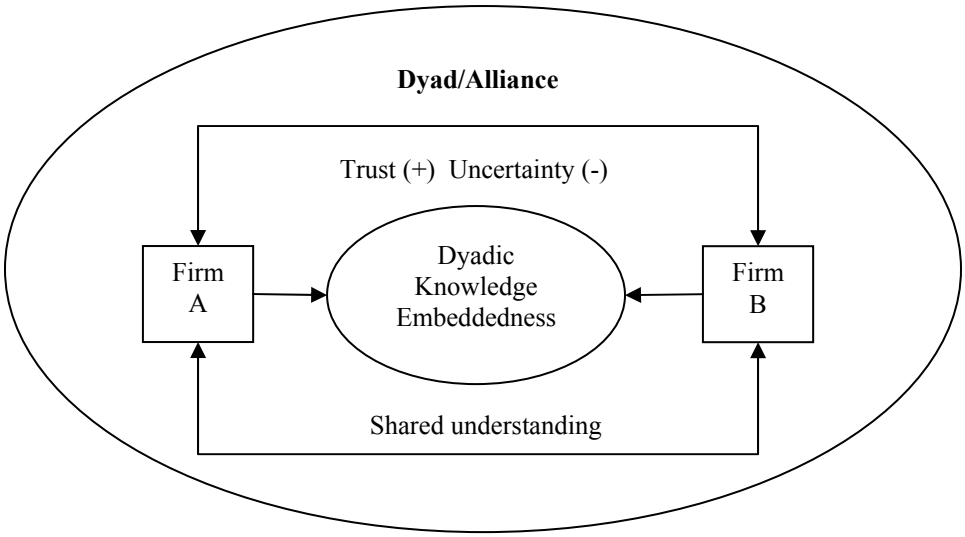


Figure 2-4: Model of dyadic knowledge embeddedness

(Source: Nielsen, 2005, p. 1196)

Nielsen's (2005) model of dyadic knowledge ebmbeddedness in Figure 2-4 shows how the creation of synergies of knowledge takes place between two actors who are engaged in a collaborative relationship, or dyadic alliance. Although this model depicts alliances at the organizational level, it is also applicable for collaborative alliances at the individual level as well. In a dyadic alliance, mutual information sharing in both directions, from actor A to actor B, and vice versa, achieves a shared understanding of the knowledge that each actor possesses. This relationship between A and B result in new embedded knowledge because of this alliance. Also in this model, the element of trust has a positive effect on the newly created knowledge, where as the level of uncertainty has a negative impact on knowledge embeddedness. The positive effect of trust in Neilsen's model of dyadic knowledge embeddednes is another commonality shared with Coleman's theory of social closure.

Hall and Graham's (2004) theory of distributed cognition is similar to Neilsen's model of dyadic knowledge embeddedness. Their theory of distributed cognition states that there is the potential to generate new knowledge collectively by individuals who could not achieve the same if working on their own (Hall and Graham, 2004). Again, the synergetic concept of knowledge benefits arising from a collective group environment is consistent with Coleman's theory of social closure for the creation of social capital.

Although new knowledge creation occurs at the individual level, establishing dyadic alliances conducive to the generation of new knowledge requires the right context. Von Krogh, Ichihjo and Nonaka (2000) refer to this concept of creating the right context or environment to encourage knowledge creation as 'ba'. Their view is that the knowledge creation process cannot be directly managed, but can instead be encouraged

by creating the right context and environment (von Krogh, Ichihjo and Nonaka, 2000, Avary and Jyrama, 2005).

2.5.2 Interdisciplinary Knowledge Creation

One aspect of creating the right context for knowledge creation, or 'ba' (von Krogh, Ichihjo and Nonaka, 2000), is providing access to social networks that offer existing relevant knowledge and expertise as well as to other people that share the same passion and goal for the creation of new knowledge. Placement in interdisciplinary programs, such as think tanks and research centres, provide facilitation and incentives for interdisciplinary knowledge creation. They offer both a community of practice in terms of a common purpose and goals as well as complementary expertise and proximity to the people who possess such expertise (Forman and Markus, 2005).

Interdisciplinary research is often recommended in rhetoric, however researchers acknowledge that there is currently little study into the actual benefits it may provide (e.g. Barton, 2001; Lowry, Curtis and Lowry, 2004; O'Conner, Rice, Peters and Veryzer, 2003; Forman and Markus, 2005). The conclusions presented by Hkupic et al. (2002) reiterate this lack of empirical or theoretical research that provides a systematic, integrated, interdisciplinary perspective to the formal study of knowledge management. However, some recent studies by Cannella and McFadyen (2004), Hall and Graham (2004), and Malhorta (2002) integrate social network theory with the study of knowledge management and knowledge creation that help to extend the theoretical and practical understandings of the nature of knowledge creation.

The concept of interdisciplinary research implies collaboration between different disciplines and traditional domains of research. The typical University research environment has increasingly been engaging in interdisciplinary research and adapting traditional methods of research, which has generally been homogeneous, disciplinary, and hierarchical, to become more heterogeneous and interdisciplinary (Cooke, 1998; Etzkowitz and Leydesdorff, 1998; Gibson et al., 1994; Rhoten, 2005). This diversity in bridging different areas of expert knowledge and resources is consistent with the instrumental approach to the creation of social capital through social networks (Johanson, 2001) and the benefits of sparse networks that span non-redundant groups proposed by Burt's structural hole theory, which supports some of the hypotheses proposed in this research.

The acceptance of interdisciplinary research as common practice in the University research community, however, is still not wide spread (Hakala and Ylijoki, 2001; Hicks and Katz, 1996; Slaughter and Leslie, 1997). O'Conner et al. (2003) and Forman and Markus (2005) demonstrate that some academic environments have pressures that discourage interdisciplinary collaborations. Some of the factors influencing this lack of progress in adopting an interdisciplinary approach in some University research environments include the lack of funding for interdisciplinary initiatives, and an unwillingness of researchers to cross boundaries into domains of research outside of their own area of expertise. There is also an incompatibility of the incentive and reward structures offered by Universities to engage in interdisciplinary practices (Bohen and Stiles, 1998; Klein, 1999; Metzger and Zare, 1999; National Academies, 1987, 2000; Weingart, 1997, Rhoten, 2005). These findings imply that low levels of funding

negatively impacts on knowledge creation, especially in the context of interdisciplinary research. Conversely, there is a positive correlation between higher levels of funding awarded for interdisciplinary research and increased propensity for knowledge creation. This is consistent with the hypotheses that this research proposes.

2.5.3 Knowledge Creation in Research Centres

Research centres and institutes act as one of the mechanisms to facilitate interdisciplinary collaborations between researchers of different disciplinary backgrounds who share a similar interest in a particular area of research. Although social relations and alliances can form naturally as a result of routine social interactions, as proposed in the evolutionary perspective on social capital (Gabby and Leender, 2001), the formation of collaborative alliances in the University research environment are typically deliberate in nature. This follows the strategic perspective on social capital (Gabby and Leender, 2001). One of the main mechanisms that facilitate such strategic alliances in the University research environment is the research centre. A research centre is essentially a self-organized community of practice that operates outside of the traditional administrative or academic structure of the University. This self-organized administrative structure creates a suitable context and environment conducive to the knowledge creation process, which is consistent with von Krogh, Ichihjo and Nonaka's (2000) concept of 'ba'.

There are several key characteristics of a community of practice in the context of social networks that make it a suitable environment conducive to the knowledge creation

process (Davenport and Hall, 2002; Wegner and Snyder, 2000; Hall and Graham, 2004). These characteristics include informal interactions, work driven by desire to share knowledge, autonomic freedom from formal agenda imposed by external forces, self-organizing system, and are sustained by the passion, interests, and resources of the participants. Research centres exhibit these characteristics of communities of practice, which makes them a suitable mechanism to help facilitate the knowledge creation process in the University research environment.

According to Hall and Graham (2004), decisions on the size of a community of practice may determine its power to support genuine collaboration and new knowledge creation. They show that although all-inclusive membership of larger groups provides opportunities for individual learning, true knowledge capital tends to emerge in smaller less public groups with more exclusive membership (Hall and Graham, 2004). Cannella and McFadyen (2004) also show diminishing returns on knowledge creation as the number of contacts in a network increases in their study of social capital and knowledge creation in the biomedical industry. Cannella and McFadyen's (2004) study also shows that the frequency of interaction between a pair of actors, which is a measure of the strength of a relationship between two actors in a network (Wasserman and Faust, 1994), also demonstrated a similar diminishing return on knowledge creation. One rationale for this is that as the network size becomes too large, the number of relationships that each member must maintain in order to sustain a densely connected cohesive network becomes too difficult to manage. Because of limited personal resources in terms of both time and effort, the strength of relationships may be compromised in order to maintain relationships with everyone in the network. Maximizing quantity of contacts at the

expense of maintaining the strength of the relationships with these contacts is detrimental to knowledge creation since the benefits that come from a cohesive network are contingent on the presence of trust. The lack of trust due to weak relationships reduces knowledge transfer and diminishes the reciprocal benefits that arise from cohesive networks. Trust is an important aspect in Coleman's social closure theory and is the basis for the expectation and obligation of reciprocal contributions to the network (Nooteboom, 2001), and without strong cohesive relationships among members it is difficult for trust to develop.

2.5.4 Research Centres as Social Networks

The formation of research centres and institutes follows the strategic perspective of social capital creation (Gabby and Leender, 2001), which proposes that social networks are intentionally formed with the deliberate purpose of gaining strategic benefiting from the resulting social capital. A social network is comprised of a finite set of individuals, also called actors, and the associations that relate these actors to each other (Wasserman and Faust, 1994) The social networks formed by these actors and their relationships are a source of social capital (Gabby and Leenders, 2001; Burt, 1992; Coleman, 1990; Putnam, 1993). In the University research environment, the individual actors, who are researchers from a variety of academic disciplines, build new relationships in the form of membership in research centres and institutes within the University, which results in the formation of new social network structures. These research centres are purposefully created with the intention of bringing together researchers with complementary skills and

expertise, and who share specific research goals. This provides value to their members, and is consistent with the creation of social capital as a productive outcome of social networks (Gabby and Leenders, 2001). The value that these social network structures provide, in the form of access to expert knowledge of other researchers, research facilities, and other resources such as social support mechanisms, can have a positive effect on the knowledge creation productivity of the individual researchers.

2.6 Positioning Universities Between Structural Holes and Social Closure

In developing the hypotheses that examine the relationship between social network characteristics and the knowledge creation process in the University research environment, one important question arises. Where is the University's place in the spectrum between social closure and structural holes?

Network sociology has been shown to play a significant role in both innovation and the underlying learning processes (Brown and Duguid, 2000; Chiffoleau, 2005). Social networks act as a mechanism whereby knowledge and innovation can be developed (Carre et al., 1989, Chiffoleau, 2005). In the discussion so far of both the instrumental approach and the expressive approach to social capital in relation to the knowledge creation process within the University research environment, the theories on knowledge creation, at first, seem more consistent with Coleman's social closure theory of social capital creation. Cohesive networks provide valuable social support

mechanisms (Pescosolido and Georgianna, 1989), encourage trust (Nooteboom, 2001) that enables the expectation and obligation of reciprocal contributions to the research community (Portes, 1998), and increases the propensity for radical innovation and knowledge creation (Cummings, 1997; Monge and Contractor, 2000).

In addition to the aspects that support Coleman's social closure theory, there are also aspects of Burt's structural hole theory that apply to the University's research community. This follows Birley and Nicolauo's (2004) contingency approach and Johanson's (2001) theory on balance of social capital between the expressive and instrumental approaches. Interdisciplinary research is an important aspect of the research conducted at Universities, and the concept of interdisciplinary implies the merging of separate and distinct disciplines. When a researcher from one domain of research forms a collaborative alliance with a researcher from another domain, this creates a link between two otherwise disjoint disciplinary groups, which is consistent with the concept of a structural hole (Burt, 1992). Researchers that engage in interdisciplinary research have the benefit of reaching new networks that are sources of expertise and resources, often resulting in new discoveries and innovation. These non-redundant information and resource benefits are consistent with Burt's structural hole theory (Higgins, 2001).

Apart from the theoretical discussion of where the University might fit into this spectrum, there are also several practical issues regarding researchers' actual behavioural patterns to consider. Although the University's vision and policy may reflect a cooperative research environment that demonstrates a collectivist organizational culture, in practice, researchers do exhibit self-serving behaviours. This is not necessarily a negative attribute; both the instrumental and expressive approaches to social capital agree

that individuals exhibit strategic behaviour by seeking out relationships and social networks to create social capital for their own benefit (Coleman, 1990; Burt, 1992; Gabby and Leender, 1999), therefore a researcher cannot be faulted for acting out of self-interest. The difference arises in who the beneficiaries of an individual's strategic actions are. In Johanson's comparison of the two approaches to social capital creation, benefits to the individual actor are associated with Burt's structural hole theory, where as benefits to both the group and the individual are associated with Coleman's social closure theory.

Typically, the productive outputs of the researchers, although they do benefit the individual researcher, are also an important asset to the University as a whole. According to the University of Waterloo's policy on intellectual property, "an academic community values openness, sharing of ideas, and scholarly activity, and its primary goals are to increase and disseminate knowledge" (University of Waterloo, Secretariat, 2004). This community-wide benefit and cooperative environment are consistent with characteristic of Coleman's social closure theory. However, researchers also have a right to protect their own intellectual property for their own personal benefit. As a result, there are still aspects of competitive behaviour that exist within the University research community. The University acknowledges, "depending on the particular situation, however, there may be a tendency to keep one's ideas to one's self. Commercial considerations, as well as potential academic recognition, can influence decisions to share ideas and results with one's colleagues. While recognizing that such tensions can exist, the University encourages an atmosphere of openness to the greatest practical degree" (University of Waterloo, Secretariat, 2004). Therefore, from one perspective, the University's policy and vision of their organizational culture is consistent with Coleman's social closure

theory supporting cohesive networks; however, from another perspective there are still elements of competitive nature consistent with Burt's structural hole theory supporting sparsely connected networks.

2.7 Summary of Hypotheses

Based on the discussion of social networks and knowledge creation presented in this Theory Development chapter, this research proposes the several hypotheses. The hypotheses look at some of the egocentric network variables, including network size, density, and strength of relationships. The egocentric perspective of social networks refers to the analysis of the ego network. Using the terminology of network sociology, an ego network is the social network with respect to a particular actor in the overall network. The ego is the actor of central focus, while the alters are other contacts that have relationships with the focal actor. Although characteristics of the total network can also be examined, the decision of using the ego network as the level of analysis is because the positioning of this research involves aspects of both the instrumental and expressive approaches to social capital creation. In Johanson's (2001) comparison of these two approaches to social capital creation, the analysis of the ego network is common to both Burt's structural hole theory and Coleman's social closure theory, where as the analysis of total networks only applies in the case of Coleman's social closure theory but not to Burt's structural hole theory.

From a contingency perspective (Birley and Nicolaou, 2004), the University's research environment exhibits certain characteristics that are generally more consistent with Coleman's social closure theory, such as the importance of trust and reciprocal contribution to the research community. There are also characteristics that are consistent with Burt's structural hole theory, such as taking advantage of distinct research resources held by separate social groups through interdisciplinary collaboration and competitive behaviours in securing research funding and the disclosure of research ideas. The hypotheses proposed in this research reflect Johanson's (2001) balanced approach to social capital with aspects of both theories of social capital creation in social networks within the context of knowledge creation in the University's research environment.

Figure 2-5 shows a conceptual diagram of the model developed in this Theory Development chapter that illustrates the predicted effects of each explanatory factor on the productive knowledge outputs of researchers at the University proposed by the hypotheses.

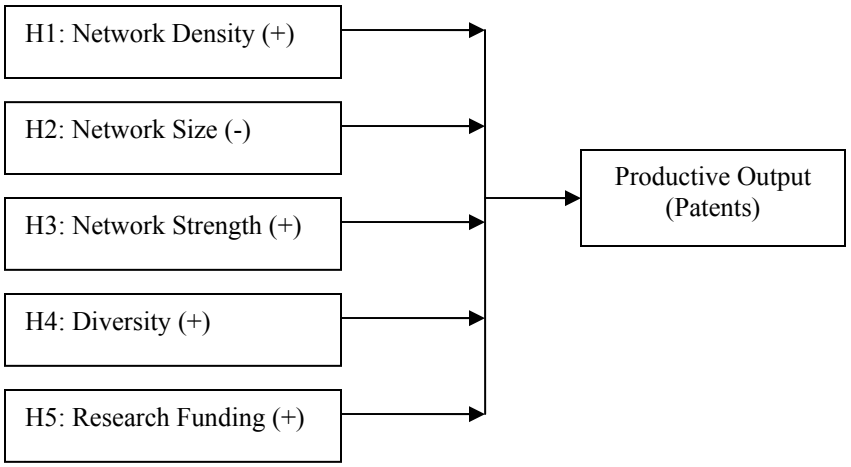


Figure 2-5: Conceptual model of hypotheses

The specific variables used to test each of these hypotheses are discussed in the following Methods chapter, which also describes the data collection techniques as well as the data analysis methods and tools used to test these hypotheses.

Hypothesis 1: Researchers who are members of denser networks have a greater propensity for patenting of intellectual capital.

Denser networks are networks that are more cohesive. These networks provide greater mechanisms that facilitate social support (Pescosolido and Georgianna, 1989). Social support and trust are forms of network content that are contingency factors that Birley and Nicolaou (2003) propose are more consistent with Coleman's social closure theory of the creation of social capital through social networks. Innovation is also another form of network content that is consistent with Coleman's social closure theory.

Based on these contingency factors, University researchers who have this social support network experience reduced levels of social and psychological stress (Lin and Ensel, 1989), and have a higher propensity for radical innovation and the new knowledge creation (Monge and Contractor, 2000; Cummings, 1997). To test this hypothesis, the model proposed by this research includes a measure of the network density of the researchers' ego network.

Hypothesis 2: Researchers who belong to large social networks have a lower propensity for patenting of intellectual capital.

The size of a community of practice affects its ability to support genuine collaboration and new knowledge creation (Hall and Graham, 2004). Network size is a contingency factor that plays a role in the balance between the instrumental and expressive approaches (Johanson, 2001) to the creation of social capital through social networks. In the case of the University research environment, researchers who have an overly large network size may have a negative effect on knowledge creation. Although larger groups with all-inclusive membership provide opportunities for individual learning, groups that are more exclusive and selective in its membership, which are smaller in size, show a higher tendency for knowledge creation to emerge (Hall and Graham, 2004). Managing large numbers of contacts requires time that may otherwise be uses conducting actual research. In addition, the reciprocal obligations of cohesive networks would also be a strain on an individual researcher's personal resources. Cannella and McFadyen (2004) show a similar result of diminishing returns on knowledge creation as the number

of relations that a researcher maintained increased in their study of social capital and knowledge creation. To test this hypothesis, the model proposed by this research includes a measure of the network size of the researchers' ego network.

Hypothesis 3: Researchers with stronger relationships within their social networks have a greater propensity for patenting of intellectual capital.

Stronger relationships help develop trust. In Coleman's social closure theory, trust facilitates the expectation and obligation of reciprocal behaviour in a cohesive social network (Coleman, 1988; Putnam, 1995; Nooteboom, 2001; Johansson, 2001). As these reciprocal associations increase within the network, the network is able to provide greater social capital to its members. In addition to reciprocal exchanges of information and resources, strong relationships within a cohesive network also help foster social support mechanisms. Researchers who have the benefit of these social support mechanisms demonstrate a higher propensity for radical innovation and new knowledge creation (Monge and Contractor, 2000; Cummings, 1997).

To test this hypothesis, the model proposed by this research includes a measure of relationship strength by looking at the average distance between contacts in the researchers' ego network. In this social network analysis, the distance between two contacts is defined by the frequency of interactions between those contacts. Wasserman and Faust (1994) define the strength of a relationship as the frequency of interaction between two actors; therefore, the average distance network characteristic is a suitable measure of the average strength of relationships in a researcher's ego network.

Although the hypothesis predicts a positive relationship between relationship strength and knowledge creation consistent with Coleman's social closure theory, there has been some contradictory evidence that shows that the increasing strength of relationships has diminishing benefits on the returns on knowledge creation (Cannella and McFadyen, 2004). An explanation for the inconsistency of this evidence with Coleman's social closure theory may be that although strong relationships do confer benefits in the form of trust, reciprocal behaviour, and social support mechanisms, similar to the hypothesis on network size, a researcher has finite limited resources. Therefore, increasing the frequency of interactions with other researchers may cease to yield additional benefits beyond a certain point because it becomes difficult to maintain these interactions due to the individual researcher's limited time and resources and may in fact hinder the researcher's individual performance when excessive resources are devoted towards maintaining a high frequency of interactions with other researchers.

Hypothesis 4: Researchers with more diverse memberships in research centres and institutes have a greater propensity for patenting of intellectual capital.

The previous three hypotheses predict social network relationships with knowledge creation that are predominantly consistent with the expressive approach to social capital involving Coleman's social closure theory. As part of the contingency approach adopted in this research, there are also aspects of this model that are consistent with the instrumental approach to social capital. Looking at network content as a contingency factor, and considering the non-redundant information and resource benefits

offered by the interdisciplinary research centres and institutes at the University, this hypothesis is more consistent with Burt's structural hole theory. According to Burt's structural hole theory, sparsely connected networks confer benefits of access to non-redundant information and resources (Burt, 1992; Johanson, 2001; Higgins, 2001). Individuals who are in positions that bridge different disciplinary groups have a competitive advantage since they are in a position that affords them the opportunity to control and access the flow of information and resources between otherwise disjoint networks. The research centres and institutes in the University comprise a set of independent groups that are otherwise disjoint from each other. Consistent with Burt's structural hole theory, individual researchers who are members of multiple research groups are in advantageous positions that bridge groups that possess non-redundant resources in terms of both expert knowledge and research resources. To test this hypothesis, the model proposed by this research includes a measure of diversity in the researchers' ego network, where the diversity factor measures the number of different research groups of which an individual researcher is a member.

Hypothesis 5: Researchers with greater access to funding have a greater propensity for patenting of intellectual capital.

Both Burt's structural hole theory and Coleman's social closure hole propose social networks provide benefits that improve the productive outcomes of its members, whether those benefits come in the form of increased access to investment capital, information, expert knowledge, trust, or social support mechanisms. The value of all

these benefits stems from the underlying implicit relationship that having more resources available as inputs results in higher levels of productive outputs. One of the benefits proposed by Burt's structural hole theory is access to investment opportunity. The implicit argument in this case is that increased access to economic and financial resources has a positive impact on productive outputs. In the University research community, although financial resources are not directly generated by social interactions with other faculty members within the University, research funding is often provided by the University itself through internal grants, by private sector sponsorships, as well as by government funding agencies, and acts as a network resource that helps facilitate research. To test this hypothesis, in addition to the specific network characteristics that previous hypotheses test, the model proposed by this research also includes a measure of research funding as an additional independent variable.

2.8 Summary of Theory Development

Through the discussion of social networks and knowledge creation presented in this chapter, the intersection of these two domains of research is evident. Both the instrumental and expressive approaches to the benefits of social capital that arise in social networks demonstrate elements of theory that relate to the theories of knowledge creation in the University research community. The model developed through this Theory Development chapter utilizes aspects of both the instrumental and expressive approaches to the creation of social capital through social networks using a balanced contingency

approach. This is consistent with both Johanson's (2001) as well as Birley and Nicolaou's (2004) previous research, which includes arguments supporting both Burt's structural hole theory as well as Coleman's social closure theory.

3 Methodology

This chapter describes the methodology employed in this study as well as the types of data collected for analysis. The first section explains the case-based context of this research, followed by a discussion on the method of data collection and the data sources involved. The next section in this chapter presents several alternatives to the actual methodology employed in this research, and explains reasons for the exclusion of these particular methods. The variable definitions are given in the following section, along with a discussion of some of the possible limitations of measures used for these variables. The final sections detail the social network and statistical regression analysis techniques used in this research.

3.1 Case Study Approach

This study examines the University of Waterloo as the case subject. The purpose of this research is to observe the relationship between certain social network characteristics and certain knowledge creation outputs. The University of Waterloo presents a good example of an organization that demonstrates strong emphasis on the research process and knowledge creation as part of its organizational activities as well as social interactions among researchers, and is therefore an appropriate example to use as the focus of study for the research presented in this thesis.

The case study approach is a common method used in research pertaining to knowledge creation in organizations, as well as in organizational social network analyses. Forman and Markus (2005) use this case study approach in their study of interdisciplinary academic collaboration. Hall and Graham (2004) also employ the case study method in their research on collaboration and generation of knowledge capital in online communities, as well as Jyrama and Ayvari (2005) in their research on managing the knowledge creation process, and Marr (2004) in his study on measuring and benchmarking intellectual capital. In Birley and Nicolaou's (2003) study of social networks in organizational emergence, they also implement a case study approach for their research.

For this case study of the University of Waterloo, the unit of analysis is the individual faculty researcher within the University. The following sections detail the types of data pertaining to the knowledge creation outputs and patterns of social interactions, as well as the sources of the data used in this research to test the hypotheses proposed in the theoretical development chapter. Next, this thesis presents a description of the data analysis techniques employed for the social network analysis and regression analysis.

3.2 Data Collection

In the investigation of social networks in relation to the knowledge creation outputs of faculty researchers, there are two different categories of data collection. The first type of

data collection entails primary data, which involves directly eliciting responses by the research subjects under investigation. The two methods of collecting primary data are via the interview process and conducting surveys. This study, however, does not use these methods of collecting primary data. Instead, this study employs an alternative method of data collection that utilizes secondary sources of data, which does not involve data about the research subjects requiring the direct elicitation of information from the subjects, but rather uses existing data about the research subjects stored in publicly accessible databases. The main reason why this study does not employ primary data collection techniques is due to the anticipated low response rates for faculty participation in interviews and surveys. In order to obtain a more complete sample population, this study uses publicly accessible sources of secondary data, which is not restricted to the willingness to participate by the faculty researchers that this study is investigating.

3.2.1 Publicly Accessible Data Sources

Obtaining a sufficient amount of primary data using the interview and survey methods previously mentioned is not a feasible part of the methodology for this research due to the anticipated low participation rates. Since participation in surveys and interviews would be an entirely voluntary process, faculty members may chose not to be involved in this study due to previous commitments with other research that they are involved with as well as other time commitments such as their academic teaching responsibilities. In addition to the anticipated low participation rates, the time required to conduct the survey and interview each faculty member individually would also pose a significant obstacle.

In order to avoid the obstacles associated with collecting primary data by means of surveys and interviews, the research presented in this thesis uses secondary sources of data that do not require direct response or participation by the individual faculty members. These secondary sources of data are stored in publicly accessible archives and directories. The benefit of using these secondary data sources is that the information regarding the individual faculty members has already been collected and consolidated in centrally located repositories that can be accessed without having to directly contact each individual member separately.

On the other hand, one of the constraints of using this type of secondary data is that the available information is limited. The exact metrics that are needed are not necessarily the ones that have been collected and recorded or publicly accessible; therefore it is necessary in some cases to reformulate hypotheses to make use of the available metrics, using the existing data as proxy indicators of the original measures of interest.

3.2.2 University of Waterloo Directory

The University of Waterloo provides an online directory (UWDIR) service that allows people to query members of the UW community such as staff, students, and faculty members. The Information Systems and Technology (IST) department at the University is responsible for the administration and maintenance of this online directory service. UWDIR allows users to submit queries based on a name and returns information

associated with that name including user id (UWID), email address, office location, office phone number, and faculty or departmental affiliation of the person being queried.

The UWID and faculty affiliation are the two important pieces of information that this study requires as part of the dataset. The UWID is a useful attribute as it provides a simple unique identifier for each member of the UW community. Having this unique identifier is important when cross-referencing and merging data from multiple data sources. The information regarding a researcher's faculty affiliation is important for categorizing the researchers. In the regression analysis, only researchers from the faculties of science and engineering are sampled for the analysis because the data for the dependent variable, PATENTS, is most relevant for these faculties since the types of knowledge and intellectual capital produced in the other faculties are not typically patented. The following section on data analysis methods discuses this faculty sampling procedure in further detail.

3.2.3 University of Waterloo Office of Research

The Office of Research (OR) is a department at the University of Waterloo that deals with issues regarding research at the University. The Office of Research outlines the policies, procedures, and guidelines governing the research practices at the University. It offers a number of programs that help members of the UW community with the research process. The Institutional Programs group oversees applications from the University for external research awards and major research infrastructure funding including applications to the Canadian Foundation for Innovation (CFI) and nominations for Canadian Research

Chairs (CRCs). The Office of Research also operates the International Programs group, which assists the University community in a variety of research and training related activities including all non-industry research and international programs.

The OR also maintains a list of the research centres, institutes, and groups that the Senate Graduate and Research Council (SGRC) has reviewed and the University's Senate has approved. As part of the guidelines for establishing a research centre or institute, each group must submit and maintain a list of its members. This study uses the membership listings of these research centres and institutes to construct a social network analysis. The regression analysis presented in this study uses the data generated by this social network analysis as well as the funding data collected from the Natural Sciences and Engineering Research Council and the patent data collected from the Canadian Intellectual Property Office.

3.2.4 Natural Sciences and Engineering Research Council

The Natural Sciences and Engineering Research Council (NSERC) of Canada is an agency under the Canadian government that helps to support Canadian Universities in achieving innovation and new discoveries in research. As part of this support, NSERC invests in close to 22,000 University students and postdoctoral fellows across Canada in their advanced studies and awards funding for new discovery and research to over 10,000 University professors each year. In addition to providing funding, NSERC also encourages more than 500 Canadian companies to support innovation by investing in University research as well (NSERC, 2005).

NSERC provides an awards search engine to access its database containing historical results if NSERC competitions and information on its funding of research initiatives since 1991. For this study, the NSERC awards search engine was queried for all awards paid out in the year 2003-2004 to any recipients who are members of the UW community. Since the dataset retrieved from the NSERC database does not contain information regarding the recipient's faculty affiliation, or whether the recipient is a student or faculty member, the results of the query are cross-referenced with the UWDIR database to filter out non-relevant records. The following section on the data analysis methods details the specific criteria for the sample selection.

3.2.5 Canadian Intellectual Property Office

The Canadian Intellectual Property Office (CIPO) is a Special Operating Agency associated with Industry Canada, which is a department of the Canadian government. The CIPO is responsible for the administration and processing of intellectual property in Canada such as patents, trademarks, copyrights, industrial designs, and integrated circuit topographies. They provide access to their database of over 75 years of patent descriptions and images, which contains over 1,500,000 patent documents (CIPO, 2005). Part of the patent descriptions includes the inventor, owner, applicant, and the file or issue dates of the patent. For this study, a list of patents associated with the University of Waterloo is generated using the CIPO patent database. The documentation for these patents lists the University of Waterloo as either the owner or applicant for the patent. Also listed in the documentation are the names of the inventors, which are cross-

reference with UWDIR to determine the UWID of the inventors so that this patent data can be merged with the funding data obtained from NSERC database and the social network data generated with research centre membership data obtained from the University of Waterloo's Office of Research.

An additional source of patent information is the US patent database. However, due to time and resource constraints, this study does not include this data source and leaves this as a possibility for future research.

3.2.6 Cross Sectional vs. Time Series Data

The NSERC funding and CIPO patent data sources provide historical data that allows for time-series analysis, however, the research centre faculty membership information from the University's Office of Research only provides current data, which only allows for cross-sectional analysis at one point in time. Although time-series data is available for some data sources, the limiting factor is the cross-sectional nature of the research centre membership data for the social network analysis; therefore, all the data used in this study is cross-sectional data that represents the state of the data at one point in time only. Since historical data is not available for all data sources, a time-series analysis is not feasible for this study.

3.3 Variable Definition

Using the data from these publicly available sources, this section defines the variables used to represent the factors that the hypotheses propose in the model. The variables in the model include DENSITY, SIZE, AVGDIST, DIVERSITY, and NSERC as the explanatory variables and PATENTS as the dependent variable.

3.3.1 Patents

In the model presented in this research, the dependent variable is PATENTS, which represents the number of occurrences that a faculty researcher has in the CIPO patent database that are either owned by or applied for by the University within a fixed time interval spanning the last ten years, from 1995 to 2005. Although the University's IP policy typically allows the creator to keep ownership rights of intellectual property, searching for patents based on a researcher's name alone, makes it difficult to verify whether the intellectual property of the patent was developed at the University. Without using the University of Waterloo as a search parameter, it is also difficult to distinguish whether or not the corresponding name in the CIPO patent database refers to the same UW researcher, since the creator name alone is not a unique identifier. Therefore, even though using the University of Waterloo as the key search parameter, as opposed to searching strictly by researcher name, limits the results returned by the CIPO patent database, this is necessary to identify patents that actually pertain to intellectual capital developed at the University. This variable is an appropriate measure of knowledge

creation output since intellectual property is one of the tangible manifestations of knowledge creation and patents are one form of readily observable intellectual property. Another reason justifying the appropriateness of PATENTS as a measure of knowledge creation in this study is that one of the rationales for the importance of this research is the value of commercialization of knowledge outputs has towards the competitive advantage of the University. A patent provides certain rights with respect to licensing and commercialization of new discoveries and innovations, and therefore the variable PATENTS used in this study is reflective of the level new and unique knowledge creation.

3.3.2 Density

The variable DENSITY represents the level of cohesion in a researcher's ego network. Network cohesion refers to the density of connectedness between all of the members in a social network. This measures the number of relations in an actor's ego network divided by the total number of pairs multiplied by 100, which is the percentage of actual relations out of the total possible number of relations in the ego network (Borgatti, Everett, & Freeman, 2002). This variable measures the construct of network density in ***Hypothesis 1***, and is an appropriate variable for this hypothesis since it is a direct measure of social network cohesion.

3.3.3 Size

The variable SIZE represents the size of a researcher's ego network. This is defined by the number of alters that the ego is directly associated with in the actor's ego network (Borgatti, Everett, & Freeman, 2002). A direct association involves the ego being in the same research group or groups as one of its alters. This variable measures the construct of network size in ***Hypothesis 2***, and is an appropriate variable for this hypothesis since this variable is a direct measure of network size as used in conventional social network analyses (Borgatti, Everett, & Freeman, 2002).

3.3.4 AvgDist

The variable AVGDIST represents the average distance between and ego and its alters in the researcher's ego network (Borgatti, Everett, & Freeman, 2002). This variable measures the construct of relationship strength in ***Hypothesis 3***, and is an appropriate variable for this hypothesis since the measure of distance between actors in this social network analysis measures the frequency of interaction between those two actors. Frequency of interaction in a relationship between two actors is an indicator of the strength of that relationship (Wasserman and Faust, 1994). In this research, the distance between two actors is equivalent to the frequency of co-membership in research centres of the two actors, and the average distance for each actor is the average frequency of co-

membership in research centres and institutes between the ego and each of the alters in the ego network.

3.3.5 Diversity

The variable DIVERSITY represents the variety of distinct types of intellectual capital resources that a faculty member is associated with by counting the number of different research groups of which each researcher is a member. This variable measures the construct of diversity of relationships in ***Hypothesis 4***, and is an appropriate variable to test this hypothesis since each research group has its own purpose and specialized domain of research and intellectual capital. The members of each research group are effectively distinct social units, each with its own area of specialized research, expertise, and intellectual capital. Therefore, this measure of DIVERSITY reflects the number of different sources of distinct expert knowledge and research resources that each faculty member has access to by virtue of their membership in these multiple research groups.

3.3.6 NSERC

The variable NSERC represents the amount of research funding received by each faculty member and measures the amount funding awarded by the Natural Science and Engineering Research Council during the fiscal year of 2003-2004. This variable measures the construct of research funding in ***Hypothesis 5***, and is an appropriate

variable for this hypothesis since the Natural Science and Engineering Council of Canada awards funding for the specific purpose of encouraging innovative research and knowledge creation in Canadian Universities.

3.3.7 Limitations

Although the measures for DENSITY, SIZE, and AVGDIST are appropriate measure for determining social network cohesion, network size, and relationship strength, one limitation of these variables is that the calculations for these social network variables are only based on potential relationships between actors within the University, as opposed to actual collaborative relationships. This study uses co-membership in research centres as a proxy metric to determine relationships between faculty members. This secondary data on research centre membership actually only provides information on potential relationships between faculty members, since membership in the same research centre provides the opportunity for collaborative research alliances but does not guarantee an actual relationship between any members of the same research centre. To determine actual relationships between faculty members, as opposed to potential relationships, this study would require primary data by directly eliciting information regarding each faculty member's research related relationships. Unfortunately, collecting this primary data was not feasible for this study; therefore, the available data was limited to secondary data sources.

A limitation of the NSERC variable is that it does not represent the total amount of research funding that a faculty member has access to. Faculty members can also have

access to funding directly from the University such as internal research grants as well as from private sector and industry sources. Unfortunately, the data for these alternate sources of research funding were not available for this study.

Another limitation is that this model only includes one measure of knowledge creation as the dependent variable. Information on patented intellectual capital only provides one perspective on the knowledge creation activities of researchers at the University. Although additional measures of knowledge creation would be useful in constructing a more comprehensive model, data on these other forms of knowledge creation were not available for this research.

3.4 Data Analysis

The data analysis methods for this study are comprised of two main components: a social network analysis of the structural characteristics within the University research community, and a statistical analysis to examine the relationship that these characteristics have with the knowledge creation outputs of the University. This section describes the details of each of these methods as well as the data sampling procedures used for each method.

3.4.1 Network Sample

To perform the social network analysis, this study uses the membership information of the research centres and institutes from the University's Office of Research and the UWDIR online directory.

The sample population for the social network analysis presented in this thesis includes faculty members at the University of Waterloo who are members of the research centres and institutes listed under Category 1 and 1A with the University's Office of Research. Table 3-1 shows the description and number of groups registered under each category.

Table 3-1: Categories of research groups

Category	Description	Count
Category 1 and 1A	Centres/Institutes with Affiliates Program - Senate Approved and Centres/Institutes/Groups within an Institute	42
Category 2	Centres/Institutes without Affiliates Program	1
Category 3	Centres/Institutes not submitted to Senate	6
Category 4	Groups	18
Category 5	Academic and Non-Academic Operating Centres, Foundations, Church College Centres	7
Category 6	External Groups	0

Category 1 and 1A account for the majority of the research centres, institutes, and groups at the University. Under the guidelines for the establishment of these centres, institutes, and groups set out by the University's Office of Research, each group has the responsibility to "promote and encourage research and related activity in an area that is not accommodated conveniently within a single academic department" (Office of Research, 2005). One of the functions of these research centres is to establish communication links within the University to facilitate the development of a particular academic area of specialization. These aspects of research centres demonstrate interdisciplinary collaboration in the pursuit of furthering the knowledge in a specialized domain. They enable relationships between faculty members of different academic disciplines to form within the construct of these research centres. These characteristics make the research centres an ideal candidate as basis for the social network analysis presented in this study.

Groups listed under categories other than 1 and 1A account for a minority of the overall groups listed by the University's Office of Research, and are not necessarily senate approved. Some of these groups do not have a strong research-based function. Therefore, to avoid including these groups in this study, the sample population is restricted to the Category 1 and 1A groups and excludes groups listed by the University's Office of Research under the other categories.

For the sample population of the social network analysis, in addition to being a member of a Category 1 and 1A research centre, each faculty member must also be present in the UWDIR online directory and listed as an active user. Names that are not present in the UWDIR online directory or that are listed as inactive may no longer be

members of the UW community, and are therefore excluded from the sample population. The total number of faculty researchers listed as members of Category 1 and 1A research centres who are also listed as active in the UWDIR online directory results in a sample population of 400 to be used for the social network analysis.

With 400 nodes in the network, it is difficult to plot the network graphically to visualize the relationships of the faculty researcher in the overall network. Instead of plotting the social network with the nodes as the individual researchers and the ties as co-membership in the research centres/institutes, Figure 3-1 shows an alternate plot of the overall social network using the research centres/institutes as the nodes and overlapping membership of researchers as the ties between nodes.

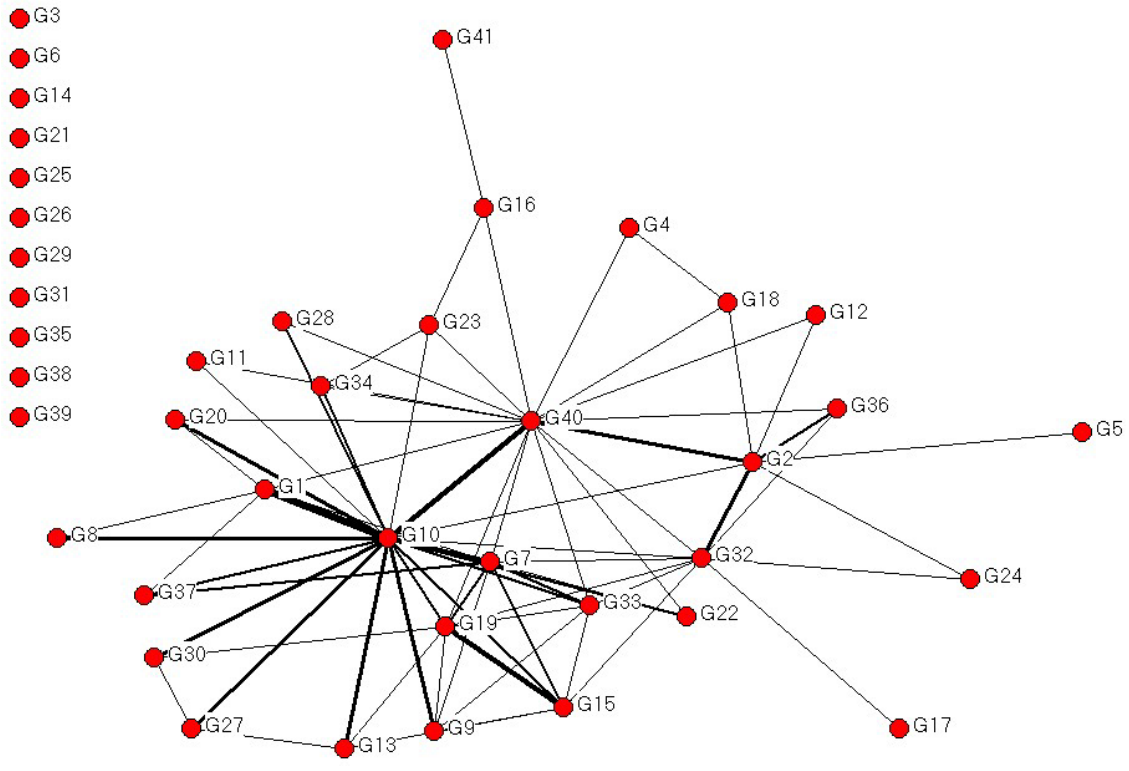


Figure 3-1: Network diagram of research centres/institutes

A thicker line indicates the ties between research centres that share a higher number of members. Research centres/institutes that do not share membership with any other centres/institutes have no ties joining them to other nodes, and appear on the left side of the Figure 3-1 in isolation from the rest of the connected network. Appendix A lists the corresponding names of the research centres and institutes for each of the labelled nodes shown in the network plot. In the network diagram, node G40, representing the Waterloo Institute for Health and Informatics Research, and node G10, which represents the Institute for Computer Research, are both central in the network and have connections to many other nodes in the network. The majority of the links connecting to the Waterloo Institute for Health and Informatics Research are weaker links, shown by the thinner lines. This indicates that there may only be one member in common linking this research group to an adjacent node, which demonstrates non-redundant connections and is a characteristic of a structural hole. Although the Institute for Computer Research is also central in the network and connected to many other nodes, these connections are much stronger, shown by the thicker lines. This indicates that there are multiple members in common between this research group and the adjacent nodes, which demonstrates high redundancy and greater network cohesion. In this case, the Institute for Computer Research exhibits structural characteristics consistent with social closure. Node G3, representing the Centre for Atmospheric Science, is isolated and not connected to any other nodes in the network. The structural characteristics of this node indicate that this research group is not in a position to benefit from social capital that arises from either structural holes or social closure.

3.4.2 Social Network Analysis

The data processing technique that this research employs to obtain the social network characteristics of the University's research community is a social network analysis using UCINET 6.0. UCINET is a software package specifically designed for the analysis of social networks and provides a number of built-in procedures to calculate a variety of social network characteristics. This software package also allows for easy analysis of data saved in Microsoft Excel spreadsheets, which is an especially useful feature for this study since all of the raw data collected is stored in Excel spreadsheets. The benefit of using the UCINET software package is that all the required calculations and algorithms to determine the social network characteristics have already been developed and implemented, and have gone through extensive testing to ensure the validity and accuracy of the network construction and analysis procedures.

Before the data can be processed with UCINET, the data to construct the social network is entered into a matrix in an EXCEL spreadsheet. A 2-mode affiliation matrix is a matrix that shows the affiliation between two different sets of items. In this case, the 2-mode affiliation matrix contains the data that relates the set of faculty researchers to the set of research centres and institutes. It lists the UWID of each faculty member in the sample population as the row headers of the matrix and the list of research groups as the column headers of the matrix. An entry of 1 is entered in the matrix for each researcher who is a member of a particular research group, and an entry of 0 if the researcher is not a member. Table 3-2 shows an example of the structure of the 2-mode affiliation matrix.

Table 3-2: Example of 2-mode affiliation matrix structure

UWID	G1	G2	G3	…	G4
asmith	1	0	0	…	1
bwong	0	1	0	…	0
chenderson	1	1	0	…	0
...	…	…	…	…	…
zoniel	0	0	0	…	1

Once the data entry of the 2-mode affiliation matrix in Excel is complete, this matrix is then imported into UCINET and ready for further data processing. A 1-mode affiliation matrix is a matrix that shows the affiliation between items from only one single set. In this study, the 1-mode affiliation matrix shows the relations between the set of faculty researchers. Each entry in the 1-mode affiliation matrix indicates the frequency of co-membership in the same research groups, which represents the strength of the relationship between researchers. An entry of 0 means that a faculty member has no research groups in common with another faculty member. An entry of 1 in the matrix means that a faculty member has one group in common with another faculty member, and similarly, an integer value representing the total number of common research groups for faculty members who have multiple groups in common. To analyze the social network characteristics, UCINET requires a 1-mode affiliation matrix containing the data on how each actor is associated with every other actor, as opposed to the 2-mode affiliation matrix that contains data on how each actor is associated to each research group. Fortunately, UCINET has the ability to construct the 1-mode affiliation matrix based on the 2-mode affiliation matrix. This data conversion procedure is equivalent to converting the 2-mode m*n matrix into a 1-mode m*m matrix by performing matrix multiplication of the original 2-mode matrix, A, with its transpose matrix, A', resulting in the 1-mode

matrix, AA'. Each entry in this 1-mode affiliation matrix denotes the frequency that each faculty member is in the same research group as another faculty member. Since co-membership is a bidirectional relationship, actor J being in the same group as actor K produces the same relationship as actor K being in the same group as actor J, therefore the resulting 1-mode matrix is symmetric. Table 3-3 shows an example of the structure of the 1-mode affiliation matrix.

Table 3-3: Example of 1-mode affiliation matrix structure

UWID	asmith	bwong	chenderson	…	zoneil
asmith	1	0	1	…	1
bwong	0	1	1	…	0
chenderson	1	1	1	…	0
...	…	…	…	…	…
zoneil	1	0	0	…	1

UCINET also provides a procedure to calculate the standard ego network measures for each actor in the network. By applying this procedure to the 1-mode affiliation matrix, UCINET generates an ego-by-variable matrix, which contains the values for each ego network measure for every actor in the network. Table 3-4 shows an example of the structure of the ego-by-variable matrix. In this matrix, the Ego is equivalent to the UWID of each faculty member in the network.

Table 3-4: Example of ego-by-variable matrix structure

Ego	Size	Ties	Pairs	Density	Avg Dist	Diameter	Nweak Comp	Pweak Comp	2Step Reach	Reach Effic
asmith	57	3192	3192	100	1	1	1	1.754386	68.42105	6.762447
bwong	83	4186	6806	61.50455	1.384954	2	1	1.204819	77.44361	6.041056
chenderson	99	5630	9702	58.02927	1.419707	2	1	1.010101	90.47619	4.544882
...	…	…	…	…	…	…	…	…	…	…
zoneil	50	2450	2450	100	1	1	1	2	87.21805	7.24849

Table 3-5 gives a description for each of the ego network measures in the ego-by-variable matrix used in the regression analysis.

Table 3-5: Description of ego network measures

Variable	Description
Size	The number of actors (alters) that ego is directly connected to.
Density	The number of ties divided by the number of pairs, times 100.
AvgDist	The average geodesic (graph-theoretic) distance between pairs of alters. This is only computed for networks in which every alter is reachable from every other.

(Source: Borgatti, Everett, & Freeman, 2002)

To test the hypotheses proposed in this study, the data for these variables are used in conjunction with the NSERC research funding data, diversity of research centre membership, and CIPO patent data for the statistical regression analysis, which is the next data analysis method that this section describes.

3.4.3 Regression Sample

The dataset used for the regression analysis is a subset of the sample population used in the social network analysis. Table 3-6 shows the number of faculty members in each academic discipline included in the sample population for the social network analysis, as well as the number of patents listed in the CIPO patent database that are associated with the members of each faculty.

Table 3-6: Number of members and patents by faculty

Faculty	Number of Faculty Members	Number of Patents
Applied Health Sciences	36	0
Arts	44	0
Engineering	118	20
Environmental Studies	15	0
Mathematics	126	0
Science	61	27

Patented intellectual capital is typically the product of researchers in the Science and Engineering faculties; therefore, it makes sense to limit the sample population for the regression analysis to faculty members of these two academic disciplines. Upon inspection of the data collected from the CIPO patent database in relation to the faculty affiliation information from the UWDIR online directory, the data collected for the dependent variable PATENTS does indeed appear to be relevant only for researchers in the faculties of Engineering and Science. Researchers in the other faculties showed no occurrences of patents in the CIPO patent database; therefore, the records for these faculty members are not relevant in the regression analysis involving PATENTS as the dependent variable. The sample population for the regression analysis is accordingly reduced to include only faculty members of Engineering and Science, resulting in a dataset containing 179 records.

3.4.4 Statistical Analysis

The data analysis technique employed in this study is a statistical regression analysis to examine the relationship between the explanatory factors proposed in the hypotheses and

the dependent variable measuring the knowledge creation output of the University in the form of patented intellectual capital. As proposed in the hypotheses, the explanatory variables are DENSITY, SIZE, AVGDIST, DIVERSITY, and NSERC, and the dependent variable is PATENTS. For the statistical analysis, this study uses a Poisson regression model. A Poisson model is a discrete linear model where the dependent variable takes on a Poisson distribution. The rationale for using a Poisson model is due to the nature of the data for the dependent variable, PATENTS. The data for this variable follows a Poisson distribution; the discrete nature, as opposed to continuous, of the data take on only non-negative integer values and is essentially count data. It also meets the three conditions for a Poisson process, listed in Table 3-7.

Table 3-7: Conditions for a Poisson process

Condition	Description
1. Independence	The number of occurrences in non-overlapping intervals is independent. Independence is required between disjoint intervals, not necessarily within the same interval.
2. Individuality	For sufficiently short time intervals, Δt, the probability of 2 or more occurrences is approximately 0, i.e. events occur singly and not in clusters.
3. Homogeneity/Uniformity	Events occur at a uniform rate over time. Therefore, the probability of an occurrence is proportional to the length of time.

Figure 3-2 shows a comparison of the distribution of the observed data from the CIPO patent database with a typical probability density function of a Poisson process. The mean for the typical Poisson distribution uses the same mean for the observed data, which has a weighted mean value of 4.62 patents per year. The distribution of the

observed CIPO patent data shown in Figure 3-2 demonstrates the same basic trend as the typical Poisson probability density function, increasing towards its maximum probability near the mean value and tapering off towards zero probability as the number of occurrences per year increases.

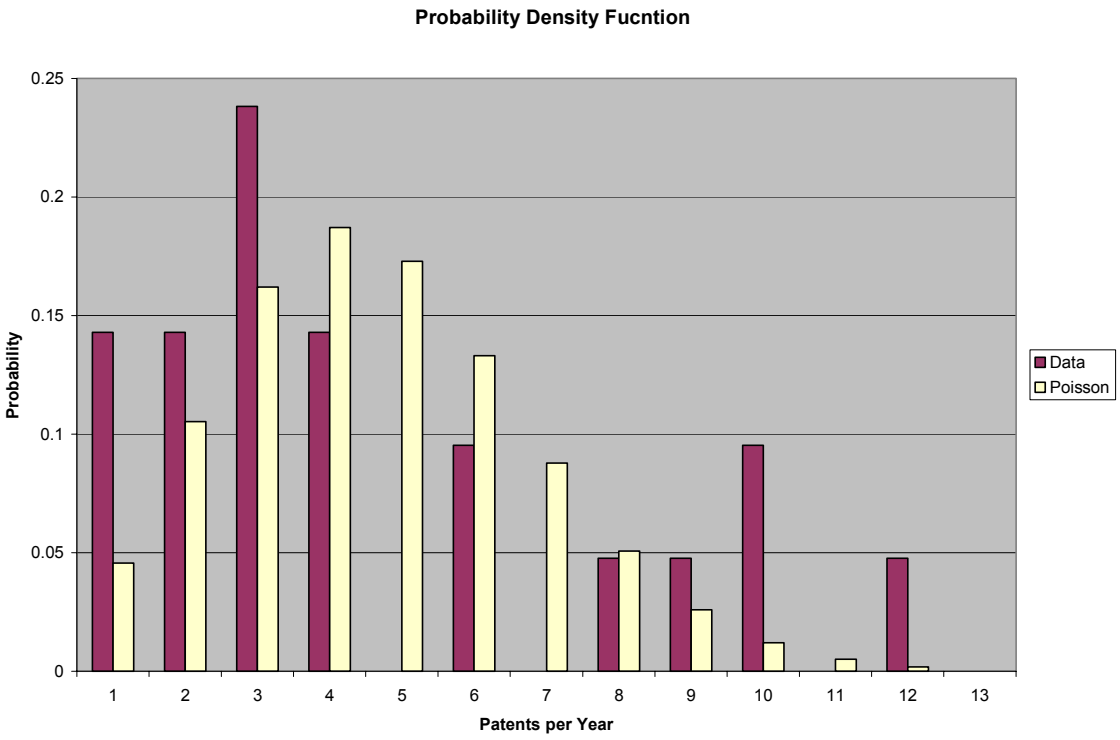


Figure 3-2: Comparison of PDF for data and typical Poisson distribution

To perform the statistical regression analysis, this study uses the SHAZAM statistical software package most commonly used for econometric analyses. The standard version of SHAZAM is a simple text-based application that provides a variety of statistical analysis tools and regression models. The most useful of these tools for this study is the MLE command, which provides the Maximum Likelihood Estimator of

regression models with non-normal error distributions, such as the Poisson distribution. The MLE command also has an additional component that allows the user to specify the type of distribution to use for the calculating the error terms in the regression. This study specifies the Poisson distribution for the MLE regression model in SHAZAM.

Table 3-8: Example of regression data structure

UWID	DENSITY	SIZE	AVGDIST	DIVERSITY	NSERC	PATENTS
asmith	145	100	1	2	18000.00	2
bwong	146	98.66792	1.013321	3	27404.00	4
chenderson	52	93.28809	1.067119	1	0.00	0
...	…	…	…	…	…	…
zoneil	184	69.07223	1.309278	2	21000.00	1

The data used for the regression analysis performed by SHAZAM is a combined dataset that uses the ego network measures calculated by the social network analysis, a measure of research centre diversity, NSERC research funding data, as well as CIPO patent data. Table 3-8 shows an example of the data structure used in the regression analysis performed by SHAZAM. The Results and Discussion chapter following in this thesis gives the results of this regression analysis.

4 Results

This chapter highlights the results of the regression analysis, showing the relationships between the explanatory factors proposed in the hypotheses and the knowledge creation outputs of researchers at the University. The initial results of the original model proposed in the hypotheses shows that only three of the five of the explanatory factors exhibit a statistically significant relationship with the dependent variable. Upon further analysis of the correlations between each of the explanatory variables, this study revises the model by eliminating one of the collinear variables from the model. The results of the regression analysis on this revised model show statistical significance for each of the four explanatory factors included in the revised model.

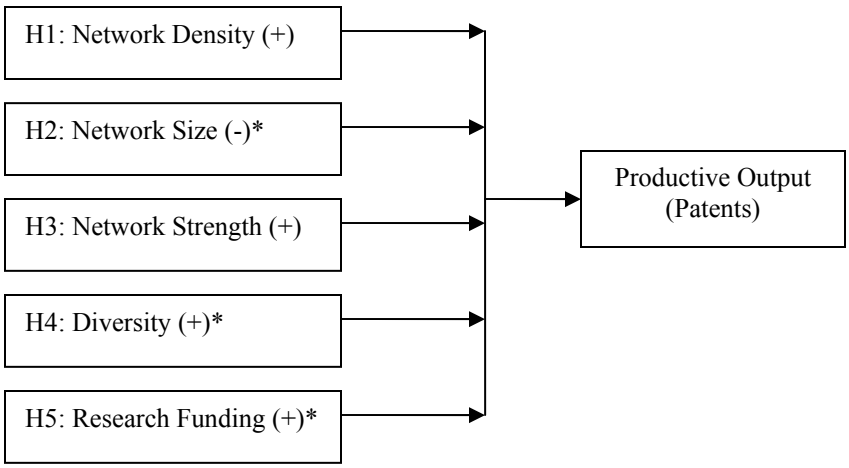
4.1 Original Model

The general form of the original model is expressed in Equation 4-1.

$$PATENTS = \beta_0 + \beta_1 DENSITY + \beta_2 SIZE + \beta_3 AVGDIST + \beta_4 DIVERSIYT + \beta_5 NSERC + \varepsilon$$

Equation 4-1: Original model

The results of this Poisson regression show that the estimated coefficients of all five of the explanatory variables have the expected sign as predicted in the hypotheses, however only SIZE, DIVERSITY, and NSERC are statistically significant, while DENSITY and AVGDIST do not appear to be statistically significant, as shown in Figure 4-1.



* Statistically significant at P<0.05

Figure 4-1: Model of hypotheses showing statistically significant results

Table 4-1 shows the results of the Poisson regression. The model includes SIZE, DENSITY, AVGDIST, DIVERSITY, and NSERC as the explanatory variables and PATENTS as the dependent variable. As proposed by the hypotheses, the results of the Poisson regression show that the knowledge creation output, using the dependent variable PATENTS, has a positive correlation with network density, strength of relationships, diversity of relationships, and the amount of research funding, and a negative correlation with network size. The results also show, however, that the correlations between the

dependent variable, PATENTS, and the explanatory variables, DENSITY and AVGDIST are not statistically significant.

Table 4-1: Results of Poisson regression

Variable Name	Estimated Coefficient	Standard Error	T-Ratio	Standardized Coefficient
DENSITY	0.0680	0.0538	1.2634	0.6925
*SIZE**	-0.0105	0.0046	-2.2629	-0.6349
AVGDIST	0.5926	4.4370	0.1336	0.0785
*DIVERSITY**	1.2688	0.4614	2.7497	0.7602
*NSERC**	0.0000	0.0000	10.4950	0.6703
Constant	-10.4960	9.5844	-1.0952	0.0000

* Statistically significant at $P<0.05$

For a further examination of the results of this regression analysis, this study also looks at the correlation between each pair of explanatory variables to check for collinearity. Table 4-2 summarizes the bivariate correlation analysis of the explanatory factors included in the model, where each value represents the correlation between the variable denoted by the column name and the variable denoted by the row name. The results of this analysis generated by the SPSS statistical software package uses Pearson's correlation coefficient as the measure of linear association between each pair of variables.

Table 4-2: Results of bivariate correlation analysis

	DENSITY	SIZE	AVGDIST	DIVERSITY	NSERC
DENSITY	1	-0.310	-0.952	-0.607	-0.083
SIZE	-0.310	1	0.261	0.604	0.066
AVGDIST	-0.952	0.261	1	0.518	0.060
DIVERSITY	-0.607	0.604	0.518	1	0.107
NSERC	-0.083	0.066	0.060	0.107	1

This bivariate correlation analysis shows that the variables DENSITY and AVGDIST are almost perfectly negatively correlated with a correlation coefficient of -0.952, indicating that they are very close to being linearly dependent variables. The mathematical calculations for these two variables do not suggest a structural reason for the collinearity between them. The calculation for DENSITY computes the proportion of actual relations in the network compared to the total number of potential relations in the network irrespective of relationship strength, where as the calculation of AVGDIST is dependent on the average frequency of interaction that defines the strength of the relationships, both of which are distinct constructs. Therefore, the nature of the observed collinearity between these two variables is an artefact of the data. Looking at the data, the mode value for AVGDIST is 1, which has a frequency of 144 out of 179 records. DENSITY has a mode value of 100, which has a frequency of 143 out of 179 records. These mode values are the minimum and maximum values for AVGDIST and DENSITY respectively. The high frequency of these values in the data accounts for the high inverse correlation between these two variables. To adjust for this, one of these variables needs to be removed from the model. Both DENSITY and AVGDIST are not statistically significant in the results of the Poisson regression for the original model. However, since AVGDIST has the lowest T-ratio and has a negligible standardized coefficient, the revised model excludes the AVGDIST variable and keeps DENSITY as an explanatory factor.

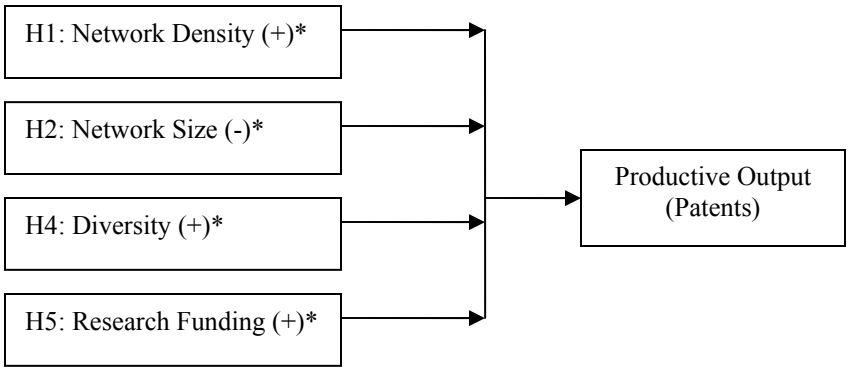
4.2 Revised Model

The general form of the revised model is expressed in Equation 4-2.

$$PATENTS = \beta_0 + \beta_1 DENSITY + \beta_2 SIZE + \beta_4 DIVERSIYT + \beta_5 NSERC + \varepsilon$$

Equation 4-2: Revised model

In the Poisson regression of the revised model, all four of the included explanatory variables appear statistically significant, and the signs of the estimated coefficients for each variable are consistent with the predicted hypotheses, as shown in Figure 4-2.



* Statistically significant at P<0.05

Figure 4-2: Revised model of hypotheses showing statistically significant results

Table 4-3 shows the results of the Poisson regression for the revised model, which excludes AVGDIST from the set of explanatory variables.

Table 4-3: Results of Poisson regression for revised model

Variable Name	Estimated Coefficient	Standard Error	T-Ratio	Standardized Coefficient
*DENSITY**	0.0620	0.0281	2.2054	0.6314
*SIZE**	-0.0104	0.0046	-2.2625	-0.6314
*DIVERSITY**	1.2641	0.4613	2.7402	0.7574
*NSERC**	0.0000	0.0000	10.4900	0.6702
Constant	-9.3009	3.1180	-2.9830	0.0000

* Statistically significant at $P<0.05$

This regression model has an R-square value of 0.51756, which represents the correlation coefficient. This correlation coefficient is a measure of the overall goodness of fit of the model, and indicates that the variation in the explanatory factors included in the model account for approximately one half of the total variation in the dependent variable. This means that there is still a large portion of the variation in the dependent variable that has yet to be explained; the next chapter on Conclusions discusses the possibility of including additional explanatory factors to help account for the remainder of the variation in the dependent variable as an area of future expansion for this research.

In the revised model, as proposed by the hypotheses, with the exception of strength of relationships which is excluded in the revised model, the explanatory factors DENSITY, DIVERSITY, and NSERC demonstrate a positive correlation with the dependent variable, PATENTS, which measures knowledge creation output, and SIZE demonstrates a negative correlation with PATENTS. Each of the explanatory variables in the revised model now shows a statistically significant correlation with the dependent variable. The magnitude of the coefficients shown in Table 4-3 are relatively small, however this is not unexpected considering the relative magnitudes of the observed data

for the explanatory variables compared to the observed data for the dependent variable. Table 4-4 highlights the descriptive statistics of the data, including the maximum and minimum values, mean, standard deviation, and number of observations in the sample.

Table 4-4: Descriptive statistics of data

	DENSITY	SIZE	AVGDIST	DIVERSITY	NSERC	PATENTS
Min	50.40	3.00	1.00	1.00	0.00	0.00
Mean	96.60	73.60	1.04	1.32	51400.00	0.26
Max	100.00	212.00	1.94	4.00	504000.00	8.00
S.D.	10.30	61.20	0.13	0.60	87000.00	1.01
N	179	179	179	179	179	179

The standardized coefficients give a better indication of the relative influence of each of the four explanatory variables on the propensity for patenting of intellectual capital. The magnitude of the standardized coefficients for DENSITY, SIZE, and NSERC range from 0.63139 to 0.67016, indicating that each of these three factors have a relatively similar influence on the dependent variable. DIVERSITY has a slightly higher standardized coefficient of 0.75737, indicating that it has a greater influence on PATENTS compared to the other three explanatory variables in this revised regression model.

5 Conclusions

This final chapter discusses the results and the interpretation of the findings in terms of how they support the hypotheses and their fit with the theories presented in the extant literature on knowledge creation and social networks. It also offers some insight and advice to researchers and the University based on the results of this research. In addition, this chapter acknowledges some of the challenges and limitations that were encountered while conducting this research and offers some proposed areas of future development of this research to address these challenges and extend the scope of the research presented in this thesis. The last section in this chapter summarizes the research results and conclusions presented in this thesis.

5.1 Discussion

The results of the regression analysis of the revised model confirm four out of the five hypotheses that this research proposes. In the case of Hypothesis 3 pertaining to the strength of an individual's relationships with other actors in the network in relation to that individual's knowledge creation outputs, the revised model excludes this hypothesis due to a high correlation with network density. This indicates the presence of collinearity between these two explanatory factors. The remainder of the hypotheses included in the revised model reflect elements of both Coleman's social closer theory and Burt's

structural hole theory on the creation of social capital through social networks, which is consistent with the balanced contingency approach (Johanson, 2001; Birley and Nicolaou, 2003) adopted in this research.

5.1.1 Network Density

The regression analysis shows that network density has a positive correlation with a researcher's patented intellectual capital. This is consistent with ***Hypothesis 1*** and supports Coleman's social closure theory, which proposes that networks that are more cohesive can generate social capital benefits. Networks that are more cohesive are denser networks with a high percentage of connectedness among members within the network, and can provide greater mechanisms to facilitate trust and social support within the University research community (Pescosolido and Georgianna, 1989). As forms of network content, trust and social support are contingency factors that support the importance of social closure (Birley and Nicolaou, 2003), especially in environments that have a higher propensity for radical innovation and creation of new knowledge (Monge and Contractor, 2000; Cummings, 1997), such as the University research environment.

5.1.2 Network Size

In the regression analysis, network size shows a negative correlation with a researcher's patented intellectual capital, which is consistent with ***Hypothesis 2***. This result supports

previous research by Hall and Graham (2004), which shows that smaller communities of practices, in the context of social networks, are better able to support genuine collaboration and new knowledge creation. Cannella and McFadyen's (2004) research also shows diminishing returns on knowledge creation as the number of relations in a researcher's social network increases. This size of a social network is a contingency factor that plays a role in the balance between the instrumental and expressive approaches to social capital (Johanson, 2001). In the University research environment, researchers must reach a balance between using their own personal resources to maintain relationships within their social networks and putting those resources to use towards their actual research. Hall and Graham (2004) show that although larger groups provide increased opportunities for individual learning, groups that are more exclusive, which are smaller, have a higher tendency for the emergency of actual new knowledge.

5.1.3 Strength of Relationships

The regression analysis of the original model did not show any statistically significant relationship between the strength of relationships within a researcher's social network and the patenting of intellectual capital, as proposed in ***Hypothesis 3***. In addition to having the lowest t-ratio in the original regression model, AVGDIST also has the lowest standard coefficient, indicating that this variable has the least significance and relative influence of the five explanatory variables in the original regression model. The bivariate correlation analysis shows that the explanatory variable representing relationship strength, AVGDIST is nearly collinear with DENSITY, the explanatory variable representing

network cohesion. An examination of the data reveals that this collinearity is an artifact of the data and not a structural problem based on the calculations of these two variables. As a result of this apparent linear dependence between AVGDIST and DENSITY, as well as having the lowest significance and relative influence, the revised regression model excludes AVGDIST from the set of explanatory variables.

One of the limitations identified for the variable AVGDIST is that the social network data from secondary sources only considers potential relationships through co-membership in research centres and institutes. Therefore, the frequency of co-membership in these research centres and institutes, which is the measure of relationship strength used to calculate the variable AVGDIST, may not be a suitable proxy for actual strength of relationships within the social network. Since the linear dependency between AVGDIST and DENSITY appears to be an artifact of the data, a more accurate measure of relationship strength, as well as the other network measures, using primary data sources, may solve this problem of collinearity in the original model. Unfortunately, the data for this research was limited to only secondary sources. The Future Research section of this final chapter discusses the possibility of including primary data as part of the research methodology for future development of this research.

5.1.4 Diversity of Relationships

The results of the analysis presented in this thesis also show that researchers with more diversity in their relationships with other researchers, through their membership in multiple research centres and institutes, have a positive correlation with patenting of

intellectual capital. This finding is consistent with ***Hypothesis 4***, and supports Burt's structural hole theory of social capital. Being a member of a more diverse variety of research groups provides a researcher with access to more non-redundant information and research-related resources (Burt, 1992; Higgons, 2001), which are beneficial assets in the knowledge creation process.

5.1.5 Research Funding

In the regression analysis, the results show that the amount of research funding that a researcher has positively correlates with their patented intellectual capital, which supports ***Hypothesis 5***. The benefits of financial capital as a from of network resource that improves the productive outcomes of members within a social network is also consistent with Burt's structural hole theory. This result is not surprising since the benefits of financial capital is not restricted to its context as a resource in a social network, but is a necessary resource for research and development of new technology and knowledge in general.

5.1.6 Balance of Social Capital in Knowledge Creation

The findings on network density and network size support aspects of Coleman's social closure theory on social capital, while the findings on diversity of relationships and research funding support aspects of Burt's structural hole theory. This research

incorporates a balance of both of these dominant theories on social networks (Johanson, 2001) based on several contingency factors that exist in the University research environment. These include innovation and social support as forms of network content, as well as the need for non-redundant information and resources through interdisciplinary collaboration. In doing so, it adopts Birley and Nicolaou's (2003) contingency approach to develop a model that describes the relationships between these network factors and knowledge creation in the form of patented intellectual capital of researchers at the University. The results of this analysis support the hypotheses developed through the extant literature on social networks and knowledge creation reviewed in this research. They relate both to Coleman's social closure theory and to Burt's structural hole theory, validating the balance of both theories (Johanson, 2001) and the contingency approach (Birley and Nicolaou, 2003) used in the development of this model.

5.1.7 Goodness of Fit of the Model

Although the results of the regression analysis show that the network density and size, as well as the diversity of relationships and amount of research funding have a statistically significant relationship with the knowledge creation outputs of the University in terms of patented intellectual capital, the results of this analysis also show that the influence of these factors does not account for the entire variation in the patenting of intellectual capital. In the Poisson regression analysis, the revised model produces an R-square value of 0.51756, which represents the correlation coefficient. This correlation coefficient expresses the goodness of fit of the model, and indicates the how well the observed data

fits with the proposed model based on the residual values between the observed data and the fitted model. In this case, the interpretation of this coefficient indicates that the variation in the data for the explanatory variables only accounts for about half of the variation in the dependent variable, PATENTS. This is not unexpected, as the set of explanatory factors chosen for the model only pertain to social network related factors. There are other possible explanatory factors that affect knowledge creation outputs outside of the scope of this research that are not included in this model. This research does, however, acknowledge the presence other factors involved that contribute to the remainder of the variation in the dependent variable, PATENTS, which are not included in this model.

In addition to the explanatory factors that the model includes, the type of model used to explore the relationship between social networks and knowledge creation is another consideration for future research. The next section in this chapter further addresses these issues in the Future Research section, which proposes that a wider variety of explanatory factors be included in future extensions of this research, as well as the use of non-linear models. The Challenges and Limitations section following in this chapter also acknowledges that this research is limited to only several key social network related factors that were identified in the Theory Development chapter, which only looked at knowledge creation specifically within the scope of a social network perspective.

5.2 Insight and Advice

Although the results of this study are not meant as prescriptive solutions for directly improving the knowledge creation practices of researchers at the University, this research does provide some valuable insight into the relationship that social networks have in the knowledge creation process.

The first general comment is that a researcher's social network can influence his or her ability for innovation and knowledge creation. Although this study was only able to look at knowledge creation in terms of patented intellectual capital, the theory behind the relationship between the benefits of social networks and knowledge creation, along with the supporting evidence of this study with respect to patents, suggest a broader applicability of the results. Future research involving other measures of knowledge creation would help validate the generalizability of these results.

The most significant finding of this study was the influence of having diverse types of relationships in a researcher's social network. It is important for a researcher to have a broad variety of expertise within his or her social network. This finding is consistent with the importance of interdisciplinary research. Innovation and knowledge creation often occurs at the intersection of disciplinary domains. Researchers should include members of other disciplines in their social networks and participate in research centres in order to take advantage of their various areas of expertise and resources. Including only members of the same disciplinary background limits a researcher's access to diverse knowledge, which can hinder innovation and the creation of new knowledge.

The finding on network size should also be a consideration for researchers. The results of this study show a negative relationship between network size and knowledge creation. However, this is not to say that researchers should minimize their social networks. Instead, the advice in this case is for researchers to be careful not to overextend their social networks. Maintaining relationships with an excessive number of contacts can be a drain on a researcher's time and resources, which can be detrimental to his or her ability to conduct research effectively.

As another consideration, researchers should also try to maintain cohesive networks. The results of this study show a positive correlation between network density, which is a measure of network cohesion, and patenting of intellectual capital. In general, previous research in the extant literature shows that cohesive networks are conducive to innovation. Cohesive networks also provide mechanism for social support and trust. The advice to researchers with respect to maintaining cohesive networks is that the element of trust and reciprocity are integral in obtaining social capital benefits from the network. A researcher must be willing to give back to other members of their research community and not selfishly abuse network resources. Abuse of the network can result in decreased cohesion and eventually sever important ties to members in the network who possess valuable knowledge and other resources. Therefore, a co-operative mentality is necessary for the success of the University's research community.

In addition to implications for the individual researchers, the results of this research are also significant from the University administration's perspective. It might be useful for the University to adapt this research to include other measures of knowledge creation and design a more prescriptive study to determine optimal network conditions. With

these findings, the University can develop new policies and strategies to encourage these optimal network conditions, which would in turn help create a more conducive environment for innovation and knowledge creation. By improving its ability to innovate, the University can improve its competitive advantage by maintaining its reputation as a leader in innovation and asserting its ability to create knowledge. This will help attract new talented and skilled researchers as well as provide an incentive for government and private sector industry to invest in future University research.

5.3 Challenges & Limitations

There were some challenges and limitations encountered while conducting the research presented in this thesis. These issues include the limited scope of the study, as well as issues concerning the data used in this research.

5.3.1 Scope of Analysis

In order to reduce the complexity of the research presented in this thesis to a manageable task, its scope has been limited to several key social network related dimensions and the relationship that these factors have on the knowledge creation outputs in academic research environments. The study of knowledge creation and knowledge management extend much further than the social network perspective presented in this thesis. Other

factors such as access to research facilities, administrative policies, organizational behaviour and culture, social networks that span interorganizational boundaries, as well as the various types of organizations are additional factors that play a role in the knowledge creation process, which were excluded from the research presented in this thesis. These factors could account for the remainder of the variation in the dependent variable PATENTS that the current explanatory factors included in the model proposed by this research does not account for. The purpose of this model is to describe the relationship between the knowledge creation outputs and the explanatory factors identified through the theory development involving social network theories in the domain of knowledge creation. However, acknowledging the role of these additional factors in the knowledge creation process, warrants further consideration in future research.

As another issue regarding the scope of this research, the relationships between the social network factors and knowledge creation outputs were limited to the case study of the University of Waterloo and only to one particular measure of knowledge creation output, patented intellectual capital. Without further research to verify the general applicability of the results presented in this thesis in the context of different of organizations and other forms of knowledge creation outputs, it is difficult to assert the generalizability of the results shown in this paper.

5.3.2 Data Collection

In addition to the limitations in the scope of this research, there are also several issues regarding the data used for the research presented in this thesis. The first major limitation is the general lack of availability of data regarding the research outputs of the University such as complete listings of publications by faculty members, licensing information, as well as entrepreneurial initiatives resulting from research conducted at the University. Although the Office of Research and Office of Technology Transfer at the University help manage much of the activity and information regarding these types of knowledge creation outputs, obtaining the actual data on these knowledge creation activities was not possible for the research presented in this study. This data would have been useful to include as additional dependent variables as alternate measures of knowledge creation outputs.

Another limitation is that only secondary sources were used to collect data, which only gives information on potential collaborations between faculty members. Because of the anticipated low participation rates, this study does not employ interview or survey methodologies to gather primary data on the research related social interactions involving actual collaborations or strategic alliances, or the knowledge creation outputs, directly from the faculty members at the University. Primary data gives a more direct measure of the interactions between faculty members and their knowledge creation outputs; this would be of value for a future extension of this research.

The third limitation is that only cross-sectional data was available for the social network analysis. Faculty membership information for the research institutes and centres

listed by the University's Office of Research were listings of current members only; historical listings of past members for previous years were not posted. Although historical data was available for the NESERC research funding and CIPO patent information, data for only one time period was used in order to align with the cross-sectional data for faculty membership in the research institutes and centres. Because of the cross-sectional nature of the data, the social network construction is only a static representation of the social networks at only one particular point in time. The actual structure social networks are dynamic in nature and subject to changes over time as the relationships and patterns of communication between individuals may change within the organization. In contrast to cross-sectional data, a longitudinal study using time-series data can follow an organizational case over time to track the structure of dynamic communication patterns and social networks, as well as changes in intellectual capital resources due to turnover trends as well as training and learning by members within the organization. The use of more historical data for time-series analysis is an area of future research, which the next section in this chapter discusses in further detail.

5.4 Future Research

In order to address some of the challenges and limitations of the research presented in this thesis, as well as to offer ideas for the future development of research into the knowledge creation process, this section proposes several possibilities for future research. These proposals include an expansion of the set of explanatory variables and measures of

knowledge creation outputs included in the model, increasing the scope to include a wider variety of organizations, and a longitudinal time-series approach to examine the dynamic relationships between social networks and knowledge creation over time.

5.4.1 Explanatory Factor Expansion

As discussed in the Challenges and Limitations section of this chapter, some other factors are identified as possible explanatory factors contributing to the knowledge creation process, which this study does not include. Because the scope of this research is only concerned with knowledge creation from a social network perspective, only several key social network related factors are included in the set of explanatory factors. This study focuses on this set of factors to examine their effect on knowledge creation outputs in the context of the University's research community. These social network factors use secondary data to determine potential relationships between researchers as a proxy for actual collaborative relationships. One of the possibilities for future research is to include explanatory factors that use primary data by incorporating interviews and surveys as part of the research methodology to measure the actual collaborative alliances and strength of relationships between researchers in the University research community. Another possibility for future research is to include the some of the other factors outside of the social network domain such as technological resources, administrative processes, government intervention, and private sector influence. By including these additional types of explanatory factors, the relative significance of each type of factor can be more closely examined and the dominant explanatory factors can be more easily identified.

In addition to the limited scope of the explanatory factors included in this model, there is also a limited measure of knowledge creation output used as the dependent variable in the model presented in this thesis. Patenting of intellectual capital is only one conservative and specific measure of knowledge creation. Aside form the data on patents from the CIPO, information on the other knowledge creation outputs of faculty members were not readily available from the University's Office of Research. Some of these other measures of knowledge creation include listings of publications of books and articles, participation in research conferences, and entrepreneurial initiatives resulting from research at University. University records pertaining to licensing, patents, and entrepreneurial initiatives by it researchers were either unavailable for use in this study or were extremely limited in the amount of available data. As this type of data becomes more accessible in the future, these measures of knowledge creation outputs can be included in future research.

5.4.2 Organizational Variety

An alternative to expanding the scope to include additional explanatory factors would be to redirect the scope of the study to examine different types of organizations, such as corporate establishments and public sector organizations or even other academic institutions. One of the contingency factors that affect the how the benefits of social capital develop through social networks is the type of network content. Each type of organization exhibits different network content in terms of the types of resources that flow through the network, the organizational culture, as well as the core competencies

and specialized activities of each organization. The type of organization and the characteristics of that organization influence the relationship between social network characteristics and the knowledge creation outputs of these organizations. In order to determine if the results of the research presented in this thesis are generalizable to other organizational environments, a broader sampling of these organizational types should be examined in future research.

Another issue regarding organizational variety is that this research only considers the analysis of social networks internal to the organizational environment. Future research could extend the scope of analysis to include inter-organizational networks that span multiple organizations, which involve both internal and external social networks at the individual and organizational level.

5.4.3 Time-Series Analysis

Another possible future expansion of this research would be to explore the relationship between social network characteristics and knowledge creation outputs from a time-series perspective using a longitudinal case study approach. The data obtained in this study is limited to cross-sectional data, which only captures the relationship between the social network characteristics and knowledge creation outputs at a single point in time. The dynamic nature of social networks over time is not observable using only a single set of cross-sectional data. By using data for multiple time periods, future research will be able to observe changes in the social network structures over time. Future studies can follow

patterns in the dynamic relationships connecting the intellectual capital resources forming the social networks any corresponding effect on knowledge creation outputs.

Because the study of social networks in the context of knowledge creation is a relatively new domain of research, there has been limited research in the area, and even less exploration into this area with respect to long-term analysis. As with any longitudinal research requiring time-series data, the first obvious necessity is time. Since there is currently little existing historical data that can be used, which is one of the limitations encountered in the data collection process of this research, this time-series data pertaining to social network structures and knowledge creation outputs must be accumulated and recorded over an extended period of time. Time-series data is important to the study of causality. Although this thesis looks at the relationships between social network characteristics and the researcher's ability to patent intellectual capital, the cross-sectional nature of this study is insufficient to determine causality. As this data becomes more readily available in the future, new studies to observe time-variant social network phenomenon in the context of knowledge creation will become more feasible.

5.4.4 Alternative Models

This study employs a regression analysis to explore the relationship between social network characteristics and knowledge creation outputs. The Poisson regression model used in the analysis is a linear model. Although this model fits well with the research presented in this thesis, the use of non-linear models that can handle relationships with a higher degree of complexity is an additional consideration for future research.

The interaction of the two sources of social capital, especially as more contingency factors are taken into consideration, may give rise to increasingly complex relationships between the explanatory factors and the productive outcomes of knowledge creation. This complexity is evident, for example, in some contradictory evidence that shows diminishing benefits on the returns on knowledge creation as the number and strength of relationships in a social network increases (Cannella and McFadyen, 2004), which is inconsistent with Coleman's social closure theory. There may in fact be an optimal level for network size and strength of relationships resulting in a U shaped relationship, which would require a non-linear model. According to Birley and Nicolaou (2003), factors such as network content, resource limitations, and organizational culture offer reasons why social network characteristics demonstrate different behaviours in terms of generating social capital under different conditions. Non-linear models provide a means to analyse these complex contingencies. They also allow for the possibility of determining optimal conditions, which is relevant in terms of organizational policy development or individual decision making by researchers such as determining how many research centres and institutes a University should establish, or knowing when your social network has become too large to manage or too small to provide any social capital benefits.

5.5 Summary

Having examined the existing theories on social networks and knowledge creation in the Theory Development chapter, this thesis develops a model including five hypotheses that involve social network factors and their relationship with the knowledge creation outputs of researchers at the University. These five factors include network density, network size, strength of relationships in the network, diversity of relationships, and research funding. The measure of knowledge creation output that these factors relate to is the patented intellectual capital of the researchers at the University. By applying a contingency approach (Birley and Nicolaou, 2003) to balance Burt's structural hole theory and Coleman's social closure theory, this research develops five hypotheses. These hypotheses propose that network density, strength of relationships, diversity of relationships, and research funding have a positive correlation with the propensity for patenting intellectual capital, while the size of the network has a negative correlation with the propensity for patenting intellectual capital.

Using data from the University's Office of Research, UWDIR online directory, NSERC research awards search engine, and CIPO patent database, this research combines social network analysis and statistical regression analysis to examine these proposed relationships. The final analysis uses a revised version of the original model that excludes relationship strength as an explanatory factor due to an issue of collinearity with the explanatory variable for network density. The results of the analysis using this revised model show that network density, diversity of relationships, and amount of research funding each have a statistically significant positive correlation with the number

of patents produced by a researcher, which is a measure of knowledge creation output, and network size has a statistically significant negative correlation with patented intellectual capital. These findings are consistent with four out of the five hypotheses developed through an examination of the existing literature pertaining to theories on social networks and knowledge creation.

In addition, the results of the analysis show that the explanatory factors included in the model do not account for the total variation in the dependent variable, which indicates that there is room for additional explanatory factors to be included in the model for future research. Because the scope of this study is limited to knowledge creation in the context of social networks, this study does not consider factors that fall outside of this particular domain of research. To address some of the limitations encountered while conducting this research, this study also proposes several ideas for future research. These include expanding the scope to include additional explanatory factors relevant to the knowledge creation process, as well as looking at different examples and types of organizations and possibly employing a longitudinal approach using time-series data.

In terms of the organizational implications of the findings of this research, understanding the relationship between social network characteristics and knowledge creation outputs is of particular importance to the University research community since the creation of new knowledge and research is one of the University's core competencies. The performance of the University, in terms of its knowledge creation outputs, has a significant impact on its economic success and competitive advantage since the University has strong ties to both government and private sector industry that often rely on the successful commercialization of the University's research outputs. By identifying

the social network characteristics that play a significant role in the knowledge creation process, the University can use this information to help improve administrative structures, policies and procedures, research incentive plans, and develop an organizational culture conducive to the creation of new knowledge and successful research.

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Appendix A: Labels for Research Centres/Institutes

Label	Category 1 and 1A Research Centre/Institute
G1	Applied Cryptographic Research, Centre for
G2	Applied Health Research, Centre for
G3	Atmospheric Science, Waterloo Centre for
G4	Business, Entrepreneurship & Technology, Centre for
G5	Canadian Centre for Arts & Technology
G6	Centre for Accounting Research and Education
G7	Centre for Computational Mathematics in Industry and Commerce
G8	Computer Communications Network
G9	Computer Graphics Laboratory
G10	Computer Research, Institute for
G11	Computer Systems Group
G12	Contact Lens Research, Centre for
G13	Control Systems Group
G14	Cultural Management, Centre for
G15	Finance, Centre for Advanced Studies in
G16	Groundwater Research, Institute for
G17	Heritage Resources Centre
G18	Innovation Research, Institute for
G19	Institute for Quantitative Finance & Insurance
G20	Institute for Quantum Computing
G21	Insurance and Pension Research, Institute for
G22	Logic Programming and Artificial Intelligence
G23	Materials Technology, Waterloo Centre for
G24	Mathematics and Computing, Centre for Education in
G25	Mid-Size City Research Centre
G26	Molecular Beams and Laser Chemistry, Centre for
G27	Nortel Networks Institute for Advanced Information Technology
G28	Pattern Analysis and Machine Intelligence
G29	Polymer Research, Institute for
G30	Programming Language Group
G31	Research Institute for Aging
G32	Risk Research, Institute for
G33	Scientific Computation Group
G34	Silicon Devices and Integrated Circuits Group
G35	Solar Thermal Engineering Centre
G36	Survey Research Centre
G37	Symbolic Computation Group
G38	Trenchless Technologies, Centre for Advancement of
G39	Waterloo Centre for the Advancement of Co-operative Education
G40	Waterloo Institute for Health Informatics Research
G41	Wetlands Research Centre