Innovation Networks and Collaboration in Canadian Nanotechnology Clusters[±]

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Abstract

This paper investigates the importance of the collaboration and social networks of inventors on the innovation generation in Canadian nanotechnology. Using information contained in 1443 nanotechnology patents of 1968 inventors we construct the Canadian nanotechnology innovation network and describe the collaborative behaviour of inventors. We find that most of the nanotechnology collaborative activity which involves Canadian inventors takes place within nanotechnology clusters. We examine the structural properties of the local collaboration subnetwork of each cluster and relate them to the efficiency of knowledge diffusion and innovation creation within that particular cluster. The majority inventors who build cooperation ties outside these clusters turn to collaborative foreign partners (mostly from the US), while only around 30% of them prefer collaborators residing in other Canadian clusters (both proximate and distant). A distance-based analysis confirms the important role of geographical proximity when searching for a cooperation partner. This importance however significantly decreases when no partners are found within 600km. Very distant or overseas collaborations are then preferred while the mid-range distance options are overlooked.

Keywords : innovation, collaboration, knowledge networks, social network analysis, patents, nanotechnology, clusters, Canada

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1. Introduction

Collective invention is a concept introduced by Allen (1983) to complement the three classical locations where an innovation takes place (which are non-profit institutions, profit-seeking firms and the minds of individual inventors). The key to understanding the phenomenon of collective invention is in the exchange and free circulation of knowledge and information within groups of socially connected (but often competing) agents rather than in the inventive efforts of particular firms or individuals. The open sharing of information thus results in a fast knowledge accumulation and high invention rates. A large number of historical examples were documented in the literature: For instance, the wide informal knowledge trading between engineers in competing minimill firms in the US steel industry was described by von Hippel (1987) and by Schrader (1991), and the knowledge sharing in a cluster of wireless communication firms in Denmark by Dahl and Pedersen (2004), but the most commonly cited example is an open knowledge sharing culture in Sillicon Valley studied by Saxenian (1994).[1]

The concept of collective invention is convenient for describing the dynamics of knowledge diffusion through various innovation networks. The network of innovators is an inter-personal network of individual innovators, who collaborate and exchange information in order to produce innovations and scientific knowledge. These are the inventors and scientists working in universities, research centers or industrial R&D departments. Social network analysis[2] has been used to analyze the way these innovators are interconnected. Within the research community investigating innovation networks, it is widely presumed that two innovators, who have worked together on at least one patent or one scientific article, will keep in touch afterwards in order to exchange information and share knowledge assets. The patent documents and bibliometric data could thus be

[1] For other examples of collective invention see Lamoreaux and Sokoloff (1997).

[2] Social network analysis is the mapping and measuring of relationships and flows between people, groups, organizations, computers or other information/knowledge processing entities. The nodes in the network are the people or groups, whereas the links show relationships or flows between the nodes. Social network analysis provides both a visual and a mathematical analysis of complex human systems (Krebs, 2006).

exploited to map the complex web of social ties among innovators and to construct the innovation networks.

The network of scientists, whose links are established by their co-authorship of scientific articles, may be the largest social network ever studied (Newman, 2001a). To our knowledge, Newman was the first to construct networks of collaboration between scientists in physics, biomedical research and computer science using four computer databases of scientific papers and to study a variety of the statistical properties of these networks to describe the network structure. In his subsequent papers (Newman, 2001b; Newman, 2001d), Newman pursued his research on the scientific networks, exploring a variety of nonlocal network properties and measures. Newman (2001c) then examined empirically the time evolution of scientific collaboration networks in physics and biology. Breschi and Lissoni (2003 and 2004) and later Balconi *et al.* (2004) constructed the network of collaborative relationships linking Italian inventors using data on co-inventorship of patents from EPO (European Patent Office). They built a bipartite graph of applicants, patents and inventors. Using this graph, they derive various measures of social proximity between cited and citing patents. Beaucage and Beaudry (2006) constructed a network of Canadian biotechnology inventors based on a similar methodology as Balconi *et al.* (2004). Cantner and Graf (2006) proposed to build the networks of innovators based on technological overlap, which is a measure of closeness of the technological field of two scientists. They also describe the evolution of the innovator network of Jena, Germany using the information on scientific mobility. Singh (2005) inferred collaborative links among individuals using social proximity graph, which he also constructed from patent collaboration data. Many other researchers[3] adopted the co-inventorship of patents as an appropriate device to derive maps of social relationships between inventors and to build their networks. Based on interviews with inventors, Fleming *et al.* (2006), however, warned that patent co-inventorship links differ significantly in their strength and information transfer capacity. Also, since their decay

[3] For instance Mariani (2000), Ejermo and Karlsson (2006); Gauvin (1995) and Fleming *et al.* (2006).

rates vary greatly, a substantial number of old ties remain viable even if the relation does not exist anymore.

The findings from the aforementioned research studies reveal some interesting properties of innovation networks. Most importantly, apparent differences in collaboration patterns according to the nature of subjects under study are observed. The characteristics of the network structures differ depending on whether they contain purely industrial or also academic researchers. Balconi *et al.* (2004) observed that networks of inventors within industrial research are usually highly fragmented. In contrast, the networks constructed by Newman (2001a) are much clustered, but since they are issued from scientific co-authorship we assume that these were mainly academic networks. Newman (2001b) also observed that for most scientific authors, the majority of the paths between them and other scientists in the network go through just one or two of their collaborators. This is in agreement with Balconi *et al.* (2004) who found that academic inventors that enter industrial research networks are, on average, more central than non-academic inventors - they exchange information with more people, across more organizations, and therefore play a key role in connecting individuals and network components. Academics also have a tendency to work within larger teams and for a larger number of applicants than non-academic inventors (Balconi *et al.*, 2004).

Newman (2001c) showed that the probability of a pair of scientists collaborating increases with the number of other collaborators they have in common, and that the probability of a particular scientist acquiring new collaborators increases with the number of his or her past collaborators. Cantner and Graf (2006) did not however find any relation between previous and present cooperation with the same partners, suggesting that collaborations in the studied region are not persistent. Former collaborations are also found to be determinant of the future success. Cowan *et al.* (2007) claimed that previous collaborations increase the probability of a successful collaboration and Fleming *et al.* (2006) argued that an inventor’s past collaboration network will strongly influence subsequent productivity.

Some of the researchers who adopted the network approach have also included geographical aspects into their models. Gittelman (2006) argues that the geography of the research collaborations has distinct impacts on firms' scientific contribution and their inventive productivity. The work of the co-located research teams results in a scientifically more valuable knowledge, whereas the more dispersed research groups are more likely to produce commercially valuable technologies. Beaucage and Beaudry (2006) also characterized three major Canadian biotechnology clusters in terms of their innovation network structures and collaborative patterns.

Another line of research related to innovation networks involves theoretical simulation studies, in which researchers build innovation network models to simulate knowledge diffusion through the network. Cowan and Jonard (2003) develop a model of knowledge diffusion and study the relationship between the network structure across which knowledge diffuses and the distribution power of the innovation system. Cowan *et al.* (2004) pursue with the simulation study of knowledge flows and compare the mean knowledge growth under different network architectures (ranging from the highly clustered to the one that has no spatial structure). In order to capture the observed practice of informal knowledge trading proposed by von Hippel (1987) and Schrader (1991) mentioned above, Cowan and Jonard (2004) model knowledge diffusion as a barter process in which agents exchange different types of knowledge only if it is mutually profitable. They examine the relationship between network architecture (characterized by different levels of path length and cliquishness) and diffusion performance. Morone and Taylor (2004) identify the limitations of Cowan and Jonard's model (2004) and improve it by introducing a network structure that changes as a consequence of interactions. They investigate the dynamics of knowledge diffusion and network formation. Finally, Cowan *et al.* (2007) model the formation of innovation networks as they emerge from bilateral decisions. They develop a model of alliance formation and examine the nature of the networks that emerge under different knowledge and information structures. One of the most important conclusions of these studies is that the existence of network structure can significantly increase long-run knowledge growth rates. The finding that the architecture of the network over which innovators interact influences the extent of diffusion and thus the innovative potential of the whole network is also the main theme of our research.

This paper aims at understanding the role of collaboration networks in the creation of innovation in Canadian nanotechnology clusters. Our research examines the diffusion of knowledge through the network of Canadian nanotechnology inventors constructed from patent co-inventorship data. The construction of the network allows us to derive the collaborative behaviour of inventors and to visualize the collaboration patterns within clusters, between clusters and outside Canada. The special focus is on network architecture, its role in knowledge generation and thus in the growth of high technology clusters in Canada. The remainder of the paper is organised as follows: section 2 introduces the methodology used in this study, section 3 presents the results describing the network of innovators and the collaborative patterns in Canadian nanotechnology in the international, inter-cluster and intra-cluster perspectives and section 4 concludes.

2. The data and methodology

In order to build the network of Canadian nanotechnology inventors we used the patent co-inventorship data contained in the Nanobank database. Nanobank is a public digital library comprising data on nanotechnology articles, patents and federal grants, as well as firms engaged in using nanotechnology commercially. The Nanobank patent database is based on the data from the United States Patents and Trademarks Office (USPTO) database. This is the only patent database which provides the geographical location of the residence for each inventor (unlike the Canadian Intellectual Property Office database (CIPO) or the European Patent Office (EPO)). The use of the USPTO database instead of the CIPO for the analysis of the Canadian nanotechnology may have caused a certain bias in the data, but we consider it minimal, since Canadian inventors usually patent both in Canada and in the US. The much larger and easily accessible nanotechnology American market offers them a greater potential than the nanotechnology market in Canada.

From the Nanobank database we have selected the patents in which at least one inventor resides in Canada (5067 patents). We have employed additional filters, which enabled us to select only the patents which are strictly related to nanotechnology[4] and

[4] For the exact description of our selection methodology see Schiffauerova and Beaudry (2008).

created a Canadian nanotechnology patent database which comprises 1443 patents. The concept of social network analysis defined above was used to create connections between all the nanotechnology inventors in these patents and to construct the networks. The use of the social network analysis program PAJEK was instrumental in building the innovation networks and in analyzing the network architectures. An analysis of these collaborative networks enabled us to understand the collaborative behaviour of the inventors in Canadian nanotechnology clusters.

Since the patent data providing us with the connections between inventors span over the period of 30 years, we have assumed that once inventors collaborate on one patent they continue to be in contact afterwards and are able to exchange information acquired long after the patent had been granted with all their collaborators. This allows us to disregard the time of collaboration and consider all links among inventors in the network as active simultaneously.

3. Canadian nanotechnology collaboration network

The main purpose of this paper consists in the study of knowledge flows and information exchange among inventors, i.e. in the characterization of the links between them. The network of Canadian nanotechnology inventors which we created includes 1968 inventors (represented by vertices) and 4920 collaborative relations[5] (represented by edges). Around 34% of all the collaborative relations between pairs of inventors involve repetitive instances of collaboration[6]. In some cases the cooperative relationships proved to be very fruitful, as the most frequent collaboration between a pair of inventors was repeated 50 times (i.e., the collaborating co-invented 50 patents together). Most of the relationships between a pair of inventors are, however, one-time collaboration instances (i.e., they resulted in only 1 patent).

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[5] Each collaborative relation (also called a tie or a link) represents a connection between a pair of inventors, which involves one or more instances of co-invention of a biotechnology patent.

[6] An instance of collaboration (or simply collaboration) is a connection between a pair of inventors for the purpose of co-invention of one biotechnology patent. Each collaborative relation may thus involve one or more instances of collaboration (collaborations).

An inventor in Canadian nanotechnology network has on average 5 collaboration partners[7], but some of them have a considerably higher number of relationship ties, the highest amounting to 54 co-inventors (see Figure 1 for the frequency distribution of collaborators). Canadian nanotechnology inventors most commonly have one (12%), two (19%), three (16%) or four (13%) collaborators. Only a small amount of inventors (4%) do not collaborate on their patent(s) with anybody else (isolates), and only a few (8%) have more than 10 co-inventors. The average numbers of collaborating partners per inventor and per patent in each cluster are presented in Table 1. The table shows that all the clusters with the exception of Toronto have a comparable average number of collaborators per inventor (around 4). The average Toronto inventor however, has around 7 collaboration partners, which suggests that Toronto inventors collaborate more intensively and exchange information with more inventors than researchers in other clusters.

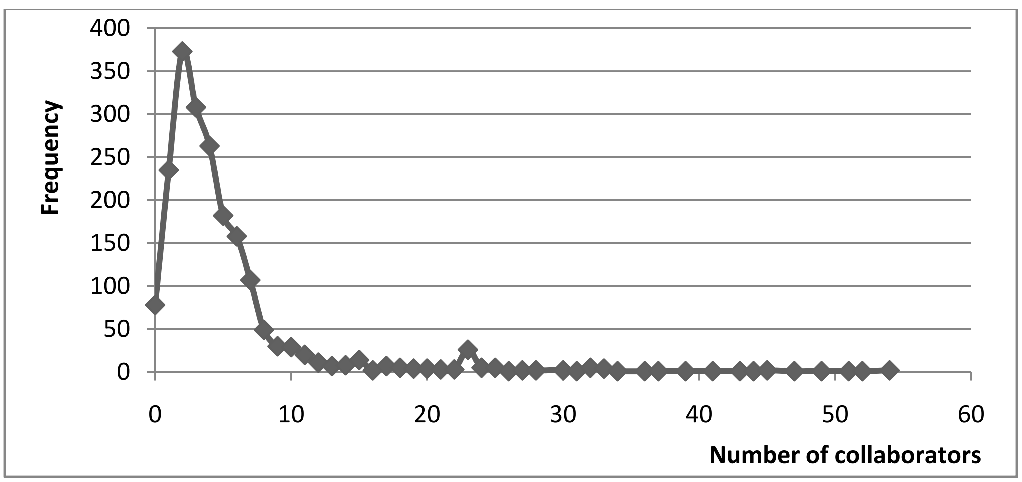


Figure 1: Frequency distribution of the number of collaborators per inventor

Our results (5 collaborators per inventor) are comparable with the average number of collaborators per inventor found by Beaucage and Beaudry (2006) who observed 5.12 collaboration partners per Canadian biotechnology inventor. We calculated the average number of collaborators per inventor for the networks of Balconi *et al.* (2004, calculated

[7] Collaboration partner (or collaborator) is here defined as a co-inventor of at least one nanotechnology patent registered at the USPTO.

from p.139, Table 5) in order to compare its value with our network. Our calculation shows that the networks of Balconi *et al.* (2004) have on average 2.09 collaborators per inventor, considerably less than the 5 collaborators observed in our network. The difference can be explained by the distinct samples of patents selected for the analysis: Contrarily to our narrowly focused patent sample (nanotechnology), in the study of Balconi *et al*, the industry range is quite broad. Newman's findings (2001a) differ even more from our results. He observed a much larger number of collaborators in his innovation networks; especially for the scientists in experimental disciplines (an average high-energy physics scientist had 173 collaborators during a five year period!). The scientific papers have however traditionally more numerous co-authors than the patents (the largest number of authors on a single paper found by Newman was 1681!), since joint article authorship was found to reflect a variety of phenomena other than the exchange of information and research collaboration.[8] Even though the legal requirements for article co-authorship and patent co-inventorship are officially very similar, the number of article co-authors is on average much higher than the number of co-inventors of the patent which reflects exactly the same discovery or invention. Ducor (2000) found that the number of article co-authors is on average more than three times higher than the number of inventors on the corresponding patent.

Table 1 shows some basic statistics regarding collaborators and collaborations in clusters. The results in the second column (co-inventors per patent) suggest that the average team size is similar in all the clusters; however ANOVA tests (in Appendix) showed that the population means are in fact different and the team sizes in Canadian nanotechnology research thus differ across the country. Balconi *et al.* (2004) proposed that they may be explained by the affiliations of the inventors – the researchers affiliated to the academic institutions work in larger teams and for a larger number of applicants than do industrial researchers. Our research does not yet distinguish between academic

[8] Cockburn and Henderson (1998) suggest that article co-authorship may be offered as a quid pro quo for supplying information or resources, it can serve as a means of resolving disputes about priority, it may also be an acknowledgement of an intellectual debt, it may just be listing of laboratory directors or other project leaders as authors or it may reflect an effort to gain legitimacy, or admission to networks of other researchers.

and industrial researchers and it is our intention to validate this hypothesis for Canadian nanotechnology in future.

The fourth column of Table 1 shows the total number of collaborative instances which involve at least one inventor of the collaborating pair who resides in the cluster. To investigate the geographical aspects of collaborations, we first classified all the instances of collaboration according to their location into *intra-cluster collaborations* (both inventors in a collaborating pair are from the cluster), *inter-cluster collaborations* (one inventor in a pair resides in a different cluster or elsewhere in Canada) and *international collaborations* (one inventor in a pair resides abroad). Figure 2 presents the overall collaboration pattern for all Canadian nanotechnology inventors. The majority (61%) of collaborations takes place within clusters and only around 12% of collaborations involve inventors from other Canadian clusters or from elsewhere in Canada. More than a quarter (27%) is formed by distant foreign ties, of which 79% are linked to American inventors.

Table 1: Statistics regarding collaborators or collaborations for each cluster

Cluster	*Collaborators per inventor*	*Co-inventors in a patent[a]:*		*Total number of collaborations*	*Collaborations per inventor*			
		All co-inventors	*Same cluster[b]*		*All*	*Intra-cluster*	*Inter-cluster*	*Inter-national*
Toronto	7.02	2.88	79%	4084	14.13	11.49	0.60	2.04
Montreal	3.97	3.07	54%	956	7.48	4.33	1.13	2.02
Ottawa	3.69	2.88	59%	645	5.34	3.47	1.27	0.60
Vancouver	3.65	2.89	79%	455	5.22	4.03	0.46	0.73
Edmonton	4.10	3.23	74%	327	6.35	4.43	1.51	0.42
Quebec	3.49	3.78	68%	161	4.81	2.77	1.00	1.04
Kingston	3.71	3.43	90%	166	6.63	3.77	2.17	0.69
Calgary	3.88	3.41	65%	187	8.55	5.76	1.79	1.00
outside	2.93	2.62	79%	504	3.61	2.21	0.77	0.64
Average in Canada	***5.00***	***3.00***	***69%***	**-**	***8.60***	***6.37***	***0.90***	***1.33***

[a] Patents were allocated to the clusters by assignees' residences. Thus only patents with at least one Canadian assignee are included.
[b] The share of inventors which reside in the same cluster as the assignee of the patent.

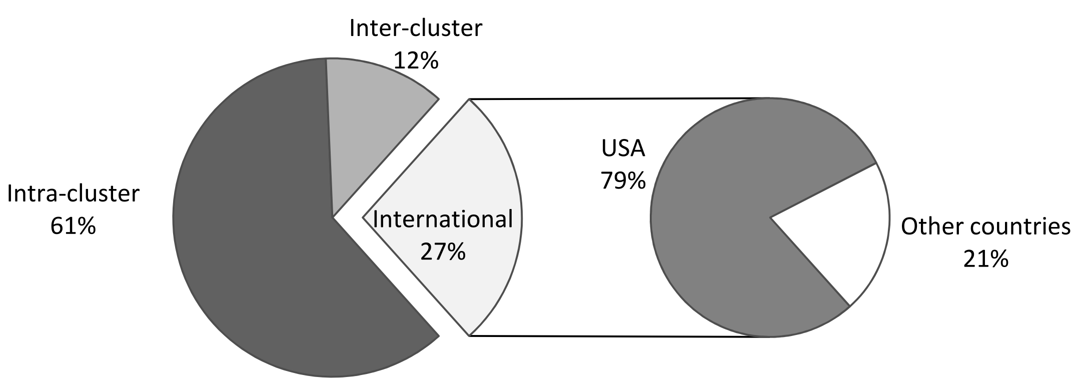
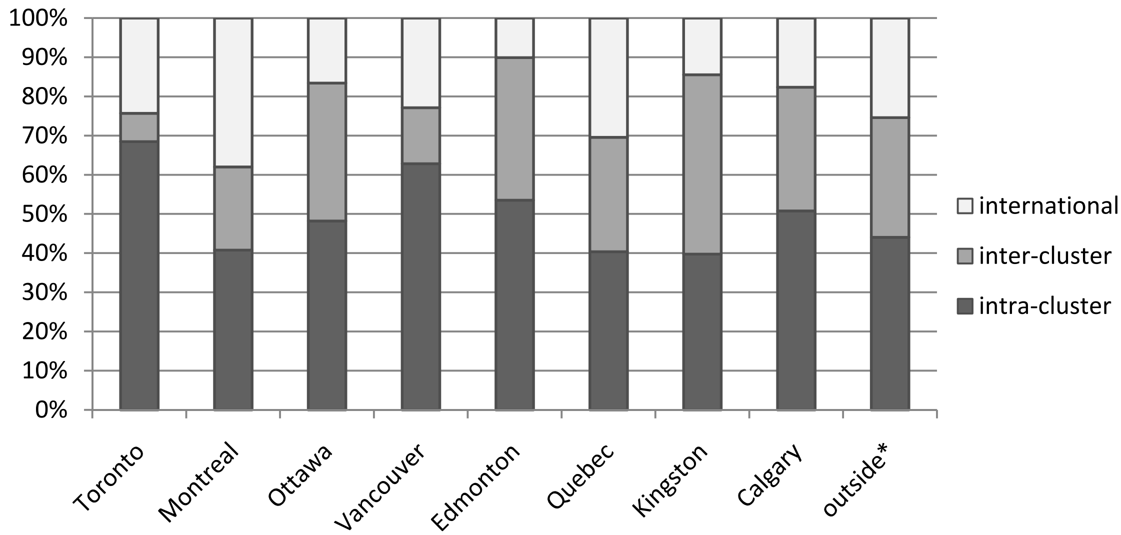


Figure 2: Collaboration pattern in Canadian nanotechnology

In order to better understand the collaborative behaviour of Canadian inventors from various clusters we have calculated separately for each cluster the exact proportions of the joint activities taking place within clusters (intra-cluster), among clusters (intra-cluster) and outside Canada (international). Figure 3 shows that in Toronto, which is the cluster with the highest number of nanotechnology inventors (41% of inventors residing in Canadian clusters are domiciled in Toronto), around 68% of collaborations between pairs of inventors take place within the cluster, where sufficient knowledge has already been accumulated. In 24% of collaborations, the expertise is sought abroad and only 7%

of collaborative ties link inventors with their partners in other clusters or elsewhere in Canada. Other nanotechnology agglomerations are much smaller than Toronto in terms of inventor counts and the percentage of their intra-cluster collaborations is lower as well (40-54%). Researchers in these clusters probably do not find all the needed expertise within their own clusters and thus have to look for collaborators outside their cluster or outside Canada more frequently. The figure also shows that some of the Canadian inventors who decide to collaborate outside their clusters prefer to do so with foreign inventors. The preference of foreign over domestic collaborators is most evident for the larger clusters (Toronto, Montreal and Edmonton) which also show the smallest percentages of collaborating pairs where each inventor comes from a distinct cluster. In smaller agglomerations however (Calgary, Edmonton, Kingston and Ottawa) inventors who wish to collaborate outside their clusters prefer to keep their collaborative ties within Canada. While interpreting the figure, recall that it represents the proportions of collaborations in each category and that the total counts of instances of collaboration differ significantly among the clusters (for the total number of collaborations see the fourth column of Table 1).

The last four columns in Table 1 present the numbers of collaborative instances for each category (intra-cluster, inter-cluster and international) normalized by the number of inventors in each cluster. Collaborative activity is the most intensive for an average inventor in Toronto; it is also high in Montreal and in some smaller clusters. The table also shows how the behaviour of the various inventors in the clusters differs. For instance, an average inventor from Toronto has over 14 collaborating experiences, around 11 of them would be found inside of his own cluster, less than 1 would come from the rest of Canada and 2 from abroad, whereas an average inventor from Ottawa would have only around 5 instances of collaboration, and majority of them (3 instances) would be from his own cluster and only less than 1 from abroad. The second and third columns of this table present similar tendencies. They show the average number of co-inventors in one patent in each cluster and the percentage of these co-inventors which reside in the same cluster as an assignee (only Canadian-assigned patents are considered here). In some clusters the proportion of the co-inventors who while living within commuting distance (within the same cluster) carried out a joint project leading to a nanotechnology patent is particularly high: In Toronto and Vancouver we found around 79% of such local collaborations, whereas for Montreal and Ottawa, this percentage is much lower (54% and 59%, respectively).



*outside: inventors residing in Canada but outside the clusters

Figure 3: Collaboration pattern of Canadian nanotechnology inventors in each cluster

In the remaining part of this paper we present the results pertaining to each of the three collaborative locations separately. We start with a bird's eye view of international collaborations in Canadian nanotechnology, then we proceed to the investigation of inter-cluster collaborations within Canada to finally focus solely on the collaborations taking place within clusters.

3.1 International collaborations

In order to understand the geographical aspects of the collaboration among the inventors we grouped the vertices into several geographically-based classes. The vertices in the following two figures (Figure 4 and Figure 5) represent all the inventors from the database grouped either by continents or by clusters. The link between each two groups shows the existence of a collaboration relation between these groups. The number associated with each link shows the total number of instances of patent co-invention for all the members of each group. To better visualize the relative differences between cooperation among the groups, the line widths represent the relative frequency of cooperation. Not surprisingly, 27% of all collaborative activities of Canadian nanotechnology inventors are carried out across Canadian border. The collaborations between Canadian and foreign inventors grouped by continents are displayed in Figure 4.

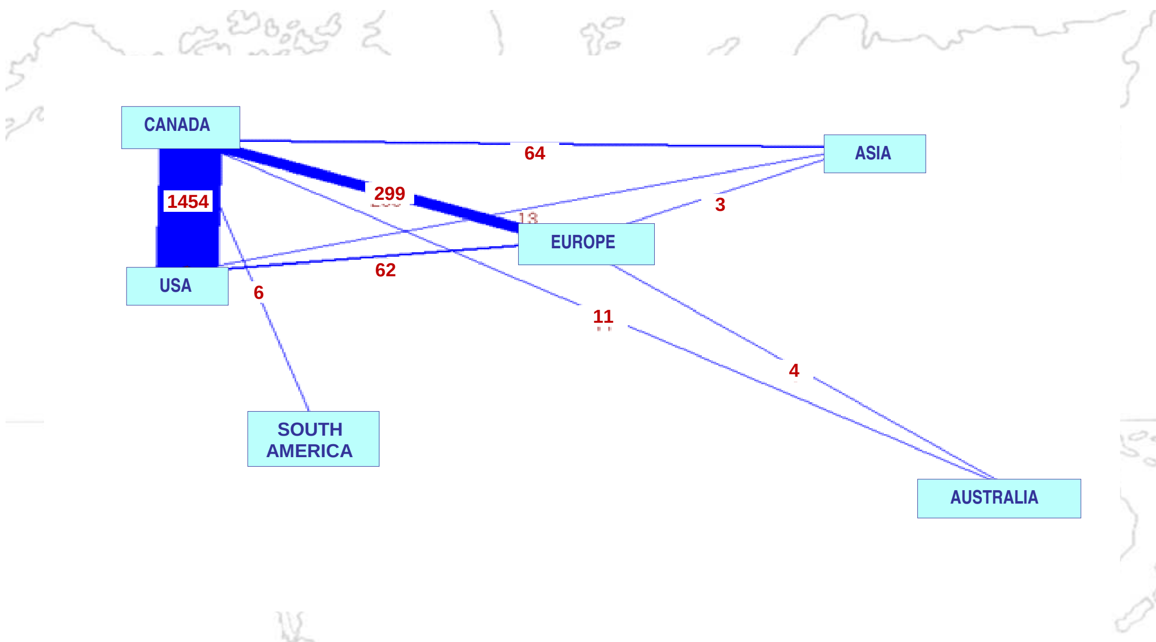


Figure 4: Collaborations between Canadian and foreign inventors grouped by continents[9]

Around 16% of cooperation ties include European countries. Among them the most frequent collaborators of Canadian inventors are French (6%), British (4%), Japanese (3%), Swedish (2%) and German (2%) inventors. Our results probably underestimate the collaboration intensity with inventors from European countries, since the joint innovative

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[9] Recall that this is restricted database that does not account for all nanotechnology patents in the world and consider the collaborations among the groups accordingly. Also, note that Canada and the USA are separated into different groups in order to provide more information even though they evidently belong to the same continent.

activity between Canadian and European inventors would most probably be better evidenced by the patents filed with the EPO or CIPO. We will therefore treat these results accordingly.

The majority (79%) of foreign collaborations of Canadian inventors clearly takes place between Canada and the USA. A more detailed geographical analysis of these partnerships in Table 2 shows the absolute and relative numbers of collaborations among the nanotechnology inventors residing in Canada and in the US regions. The most popular US cooperation partners for Canadian nanotechnology inventors reside in the Northeast (47%) region. Among the US states, the highest number of Canadian cooperation links is directed towards Ney York (35%), California (17%) and Oregon (13%).

Table 2: Number of collaborations among inventors in Canadian nanotechnology clusters and in the US regions (slightly modified US Census Regions).

	Northeast	***Northwest***	***Midwest***	***South***	***Southwest***	***ALL USA***
Toronto	**495 (56%)***	145 (16%)	43 (5%)	48 (5%)	161 (18%)	**892 (100%)**
Montreal	**61 (27%)**	**60 (26%)**	26 (11%)	40 (18%)	41 (18%)	**228 (100%)**
Ottawa	**26 (41%)**		5 (8%)	**26 (41%)**	6 (10%)	**63 (100%)**
Vancouver	11 (21%)	9 (17%)	1 (2%)	1 (2%)	**31 (58%)**	**53 (100%)**
Edmonton	6 (21%)		8 (27%)	2 (7%)	**13 (45%)**	**29 (100%)**
Quebec	14 (44%)				**18 (56%)**	**32 (100%)**
Kingston	4 (24%)	5 (29%)		**7 (41%)**	1 (6%)	**17 (100%)**
Calgary	**11 (33%)**		6 (18%)	10 (31%)	6 (18%)	**33 (100%)**
ALL CANADA	**628 (47%)**	**219 (16%)**	**89 (7%)**	**134 (10%)**	**277 (20%)**	**1347 (100%)**

* For each cluster, the percentage in parentheses shows its shares of collaborations with every US region.

The table also shows the main collaboration partners per cluster. Even though inventors from Toronto, Ottawa and Montreal look for their collaboration partners most frequently in the close Northeast region, they find attractive collaboration deals in the geographically distant South or Northwest as well. The preferences of the western clusters of Vancouver and Edmonton for the south-western US states are not surprising, but it is not at all obvious why the inventors in the western cluster of Calgary should choose to seal their partnership contracts predominantly in the eastern or southern parts of the US. These results suggest that once the deal cannot be made inside a cluster or within Canada the choice of the collaboration partner seems to depend much less on the geographical location. But how important are the geographical selection criteria when searching for a collaborator inside Canada?

3.2 Inter-cluster collaborations

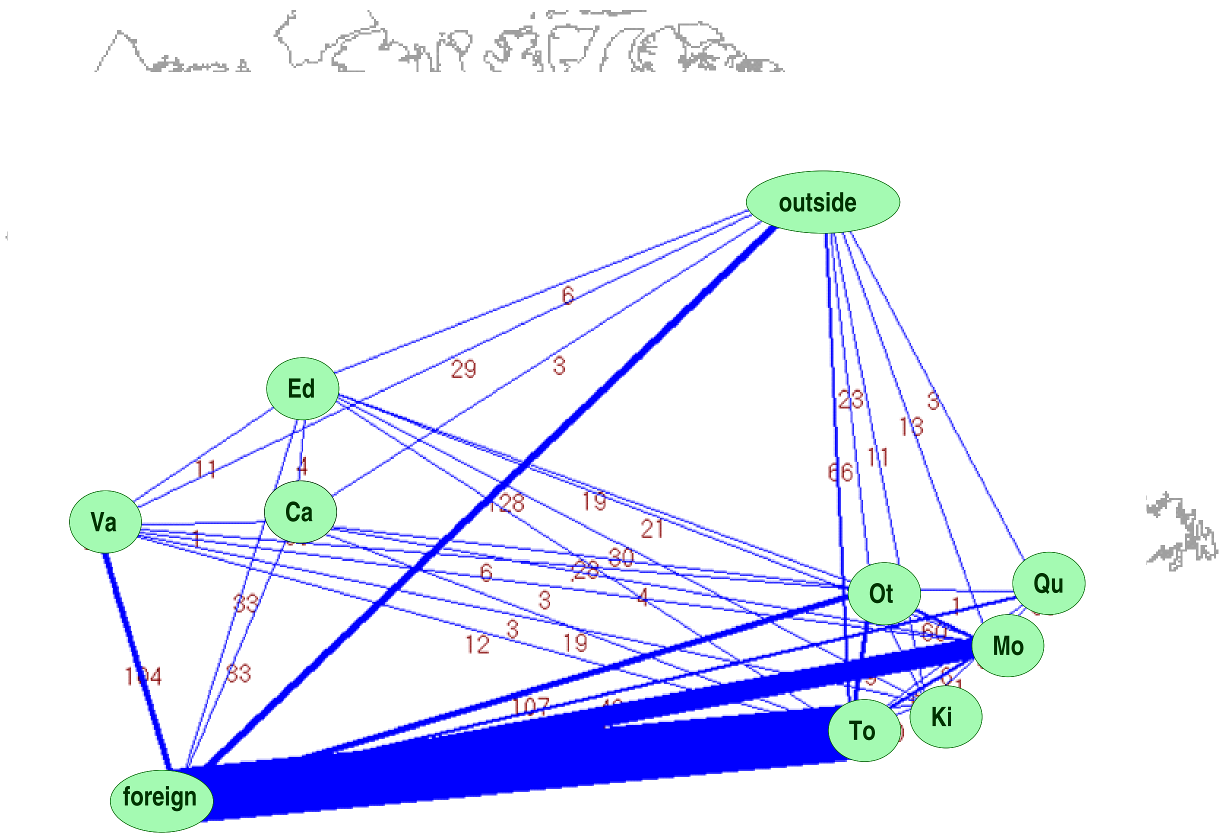
This section investigates the role of geography in the choice of a partner for joint research projects carried out within the Canadian borders. Figure 5 illustrates the collaborations among nanotechnology inventors of different Canadian clusters and the strength of the collaboration ties both among individual Canadian clusters as well as between each cluster and all foreign countries grouped together. To put the inter-cluster collaboration into perspective, we included international collaborations in the figure as well. Evidently, the same large proportion of collaboration among nanotechnology inventors takes place over the Canadian border. Canadian inventors rather pursue their joint research projects with inventors abroad, than with their colleagues from other Canadian clusters or outside these clusters, even if these reside relatively close by.

Only 12% of all collaborative activities take place among Canadian clusters. Figure 5 indeed shows that the strongest collaborations are located within the triangle formed by Toronto, Montreal and Ottawa, even though both Toronto and Montreal pursue a great deal of their joint research activities with inventors abroad. Smaller clusters however prefer collaboration with Canadian inventors. Western clusters**:** The second collaboration pattern describes the typical cooperative behaviour of the western clusters of Vancouver, Edmonton and Calgary. For the inventors in all these clusters, the most preferable collaborative partners live in the eastern part of Canada, whereas the innovation partnerships from the geographically closest clusters are usually much less attractive. Vancouver's inter-cluster research partnerships are forged mainly with inventors from the distant Toronto, but also from geographically close Edmonton. Edmonton's collaborative ties are however directed predominantly towards the east: Kingston, Toronto, Montreal and Ottawa, while only a very small interest in proximate collaborative partnerships is observed. Similarly as Edmonton, the Calgary's geographically close cooperation ties are weak, and the collaboration with Eastern clusters is much more common, particularly with Ottawa and Toronto. The preferable cooperation partners of the inventors in the

Western clusters are found usually in the Eastern clusters, while local and geographically close partnerships are relatively limited.

Note that in Table 3, a large portion of the collaboration ties in Vancouver and Toronto are directed outside the clusters. These are partly the result of our cluster definitions. Victoria hosts a nanotechnology agglomeration, which was geographically too far to be included within the Vancouver cluster and too small to stand on its own. Consequently, many Victoria inventors often contribute to joint research projects with Vancouver inventors, but are considered to be residing outside the cluster. In fact, 84% of inventors living outside clusters in British Columbia live in Victoria. The situation is similar with the Toronto cluster, which is geographically restricted to the areas extending until Hamilton and Kitchener on the south-western side, but does not reach as far as London. Around 34% of the inventors from outside clusters in Ontario reside in London. In order to create a clearer picture of the described collaborative patterns we added up together all the links leading to the Eastern clusters as well as the ones which are connected with the Western clusters. The results are displayed in **Error! Reference source not found.**. The ties directed outside clusters were divided into the Western-outside ties (leading to inventors living outside the defined clusters, but within British Columbia or Alberta) and Eastern-outside ties (directed towards inventors living outside the defined clusters, but within Ontario or Quebec), while the remaining ties leading to outside of the four main provinces were eliminated completely. The figure demonstrates the prevalent tendency of Eastern clusters to search for geographically proximate partnerships and the priority of Western clusters cooperate with the Eastern clusters.

Table 3 reveals a more detailed picture of the inter-cluster cooperation in Canadian nanotechnology. We have observed that the collaborative behaviour of the inventors in Canadian nanotechnology clusters follows two geographically distinct collaborative patterns. Accordingly we have divided the defined nanotechnology clusters into two groups: Eastern clusters and Western clusters.



Va	…Vancouver	Ed	…Edmonton	Ca	…Calgary	To	…Toronto
Ot	…Ottawa	Ki	…Kingston	Mo	…Montreal	Qu	…Quebec

outside …group of inventors residing in Canada, but outside clusters
foreign …group of other non-Canadian inventors

Figure 5: Collaborations among Canadian inventors grouped by clusters

***Eastern clusters*:** The inventors in the nanotechnology agglomerations of the eastern part of Canada (Toronto, Montreal, Ottawa, Quebec and Kingston) mostly pursue an expected collaborative behaviour, which is to look for the cooperation partnerships within a relatively short distance of their own cluster. Toronto's most important collaboration partners are Ottawa and Montreal, while the inventors in Montreal collaborate mostly with the researchers from Toronto, Ottawa and Quebec; in case of Ottawa the collaborators are mainly from Toronto and Montreal, and finally the Quebec's inventors seek their cooperation partnerships usually in Montreal. The links with the highest number of collaboration instances in the whole Canadian inter-cluster collaborative network involve the cooperative triangle of Toronto-Montreal-Ottawa (Toronto-Ottawa link: 79 instances, Toronto-Montreal link: 64 instances and Montreal-Ottawa link: 60 instances). The small Kingston cluster is partially an exception in this group: Even though its researchers often find their partners in the geographically proximate clusters of Toronto and Ottawa, they also maintain important cooperative initiatives with the distant western cluster of Edmonton as well. As a general pattern, however, inventors in the Eastern nanotechnology clusters do not collaborate much with the western part of Canada and prefer to seek local or geographically close partnerships.

***Western clusters*:** The second collaboration pattern describes the typical cooperative behaviour of the western clusters of Vancouver, Edmonton and Calgary. For the inventors in all these clusters, the most preferable collaborative partners live in the eastern part of Canada, whereas the innovation partnerships from the geographically closest clusters are usually much less attractive. Vancouver's inter-cluster research partnerships are forged mainly with inventors from the distant Toronto, but also from geographically close Edmonton. Edmonton's collaborative ties are however directed predominantly towards the east: Kingston, Toronto, Montreal and Ottawa, while only a very small interest in proximate collaborative partnerships is observed. Similarly as Edmonton, the Calgary's geographically close cooperation ties are weak, and the collaboration with Eastern clusters is much more common, particularly with Ottawa and Toronto. The preferable cooperation partners of the inventors in the Western clusters are found usually in the Eastern clusters, while local and geographically close partnerships are relatively limited.

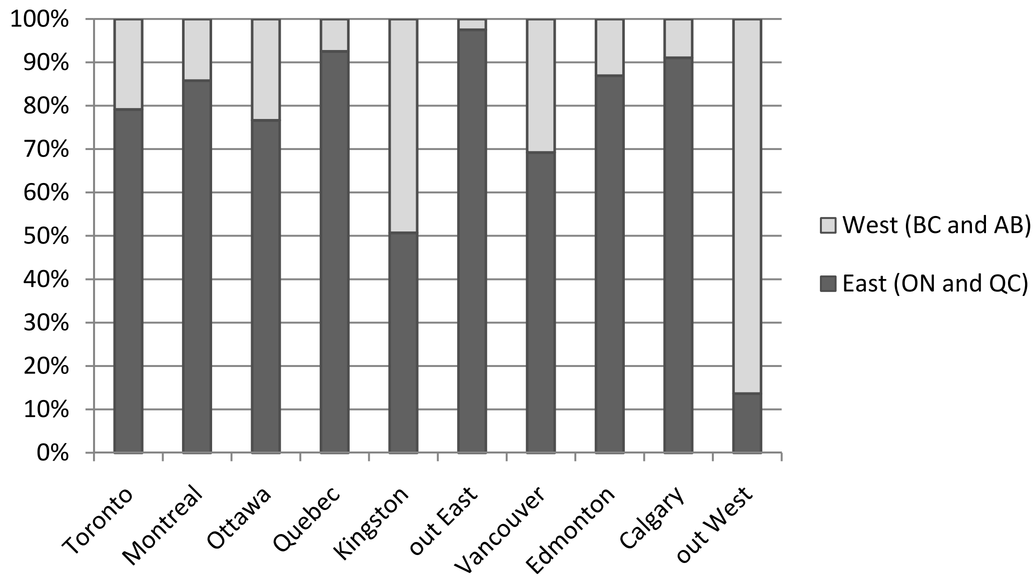
Note that in Table 3, a large portion of the collaboration ties in Vancouver and Toronto are directed outside the clusters. These are partly the result of our cluster definitions. Victoria hosts a nanotechnology agglomeration, which was geographically too far to be included within the Vancouver cluster and too small to stand on its own. Consequently, many Victoria inventors often contribute to joint research projects with Vancouver inventors, but are considered to be residing outside the cluster. In fact, 84% of inventors living outside clusters in British Columbia live in Victoria. The situation is similar with the Toronto cluster, which is geographically restricted to the areas extending until Hamilton and Kitchener on the south-western side, but does not reach as far as London. Around 34% of the inventors from outside clusters in Ontario reside in London. In order to create a clearer picture of the described collaborative patterns we added up together all the links leading to the Eastern clusters as well as the ones which are connected with the Western clusters. The results are displayed in **Error! Reference source not found.**. The ties directed outside clusters were divided into the Western-outside ties (leading to inventors living outside the defined clusters, but within British Columbia or Alberta) and Eastern-outside ties (directed towards inventors living outside the defined clusters, but within Ontario or Quebec), while the remaining ties leading to outside of the four main provinces were eliminated completely. The figure demonstrates the prevalent tendency of Eastern clusters to search for geographically proximate partnerships and the priority of Western clusters cooperate with the Eastern clusters.

Table 3: Number of collaborations among nanotechnology clusters in Canada

	Eastern clusters (with predominantly local partnerships)					***Western clusters (with mainly eastern partnerships)***		
	Toronto	*Montreal*	*Ottawa*	*Quebec*	*Kingston*	*Vancouver*	*Edmonton*	*Calgary*
Toronto		**64 (32%)**	**79 (35%)**	6 (13%)	**20 (26%)**	**12 (18%)**	**28 (24%)**	**19 (32%)**
Montreal	**64 (22%)***		**60 (27%)**	**37 (79%)**	1 (1%)	3 (5%)	**21 (18%)**	4 (7%)
Ottawa	**79 (27%)**	**60 (30%)**		1 (2%)	**11 (15%)**	6 (9%)	**19 (16%)**	**28 (47%)**
Quebec	6 (2%)	**37 (18%)**						
Kingston	20 (7%)	1 (1%)	11 (5%)			3 (5%)	**30 (25%)**	
Vancouver	12 (4%)	3 (1%)	6 (3%)		3 (4%)		11 (9%)	1 (2%)
Edmonton	28 (10%)	21 (10%)	19 (8%)		**30 (39%)**	**11 (16%)**		4 (7%)
Calgary	19 (6%)	4 (2%)	28 (12%)			1 (2%)	4 (3%)	
out	**66 (22%)**	13 (6%)	23 (10%)	3 (6%)	11 (15%)	**29 (45%)**	6 (5%)	3 (5%)
ALL	***294 (100%)***	***203 (100%)***	***227 (100%)***	***47 (100%)***	***76 (100%)***	***65 100%)***	***119 (100%)***	***59 (100%)***

* For each cluster, the percentage in parentheses shows its shares of collaborations with other clusters.

All in all, Toronto is by far the most popular cooperation partner for Canadian nanotechnology inventors from other clusters or elsewhere. Indeed, 24% of all inter-cluster collaboration links in the whole network are directed towards the Toronto cluster. It is followed by Ottawa (18% of links), Montreal (16%) and Edmonton (10%). Vancouver seems to be a less attractive region for joint nanotechnology research for Canadian inventors, since it accounts only for 5% of the collaborative links in the inter-cluster network. The conclusion stemming from this analysis is that the geographical distance is not likely to be the only critical factor when seeking partners outside the cluster. Other probably decisive factors are the availability of particular inventors' nanotechnology specialization and expertise, the size and reputation of nanotechnology research, available facilities and funding, etc.



West…includes all collaboration ties directed to the inventors living in British Columbia and Alberta
East….includes all collaboration ties directed to the inventors living in Ontario and Quebec
out West… collaboration ties directed to the inventors living outside the defined clusters, but within British Columbia or Alberta
out East… collaboration ties directed to the inventors living outside the defined clusters, but within Ontario or Quebec

Figure 6: The cooperation of each cluster with the Eastern and Western cluster groups

3.3 Distance-based analysis of all out-of-cluster collaborations

Given the specific geographical aspects of Canada, i.e. concentration of a great majority of its inhabitants along the southern border, the collaboration analysis based on political divisions (e.g., national versus international cooperation) does not actually tell the complete story about the distances between collaboration partners. Many Canadian nanotechnology clusters are located in proximity of the US border and an international collaboration partner can thus be the closest one. For example, a Montreal inventor may find it much more convenient to establish a collaborative partnership with his international counterpart in Boston than with a fellow Canadian inventor from Vancouver, since the distance is almost 10 times shorter. We have therefore divided all the out-of-cluster collaborations (including both international and inter-cluster ones) into four groups according to the distance between the residences of each collaborative pair: short range (< 600km), mid-range (600km to 1600km), long range (> 1600km) and overseas (outside North America). Figure 7 shows the proportions of these collaborations for the inventors in each cluster. Out of the larger clusters, Toronto (55%) and Ottawa (58%) have the highest percentages of short range collaborations, whereas the proximate cooperation projects do not seem to be popular in western clusters of Vancouver (7%), Calgary (6%) or Edmonton (3%). The low level of inter-cluster collaboration among the western clusters has already been suggested as well as their preference for partners from South-western or North-eastern US regions. The figure confirms very high shares (Calgary 88%, Edmonton 86%) of the long-range partnership for the western clusters. In all the greater clusters, the proportions of the long-range and overseas collaborations are also substantial, but the projects carried out over the mid-range distances do not seem to be that common.

Almost 50% of out-of-cluster collaborations of Canadian inventors involve partners residing at more than 1600km of distance. Most of these distant partners live in Canada or the USA, but almost 30% of these collaborations link Canadians with overseas inventors. Mid-range collaborations are considerably less popular, only around 8% of all collaborations outside clusters are carried out within the 600km-1600km range. Joint research projects with geographically more proximate partners are much more frequent. In 44% of cases the out-of-cluster collaboration involves a partner located within a distance of a maximum of 600km.

Taking into consideration our results, we conclude that the geographical distance plays an important role when deciding on partners for joint research projects in nanotechnology. We observe an overwhelming preference of the Canadian inventors towards local and regional partnerships, especially within their own nanotechnology clusters. However, if the suitable collaborators are not found within the region or at a short-range distance, the geographical criterion loses its importance. Inventors then quite often prefer very distant or overseas cooperation while disregarding the mid-range options. Other factors (nanotechnology specialization, particular expertise, available facilities, previous acquaintance – e.g. former PhD supervisor, etc.) then become more prominent in explaining the inventors' choices.

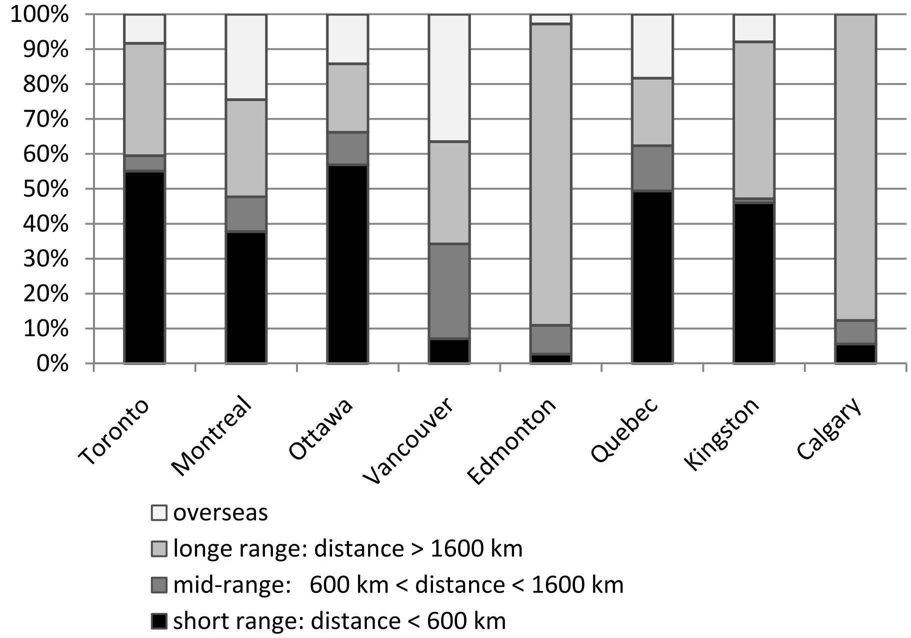


Figure 7: Proportions of all out-of-cluster collaborations (including both international and inter-cluster cooperation) based on the distance between the collaborators[10]

3.4 Intra-cluster collaborations

It has been suggested and empirically supported that firms in clusters are more innovative (Baptista and Swann, 1998; Beaudry, 2001; Beaudry and Breschi, 2003; Beaudry and Swann, forthcoming). Companies collocated in close geographical proximity enjoy numerous benefits[11], among which the most discussed in the context of biotechnology innovation are knowledge spillovers[12]. Nanotechnology knowledge is

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[10] The distances are approximate: They are measured from the metropolitan centre of the Canadian clusters or from the geographical centre of the US states.

[11] Supply-side benefits were defined by Krugman (1991) as labour market pooling, availability of immediate inputs and knowledge spillovers, while Baptista and Swann (1998) who surveyed demand-side benefits indicated that the major ones are strong local demand, market share gain, decreased search costs, and exploitation of local information flows.

[12] Localized knowledge spillovers are defined as knowledge externalities bounded in space that allow companies operating nearby key knowledge sources to introduce innovations at a faster rate than rival firms located elsewhere (Breschi and Lissoni, 2001).

largely tacit, which limits knowledge diffusion over long distances. In fact, the transmission of tacit information and knowledge spillovers is usually associated with face-to-face contact. Collaboration among inventors working in clusters is thus encouraged by the benefits of acquiring knowledge which the subjects located within short geographical distance spill over. Indeed, we show that 61% of collaboration activities in Canadian nanotechnology are carried out within clusters (see Figure 2). This section of the paper analyzes these local collaborations carried out entirely within clusters. We have divided the Canadian nanotechnology innovation network into geographically based subnetworks, where each subnetwork strictly includes inventors who reside in one particular cluster, while excluding the ones that do not. Out of cluster inventors are therefore eliminated for the time being. For each of the subnetworks created in this manner several network characteristics were calculated. Table 4 presents some of these properties. The following part briefly discusses several of the basic structural properties of the network and explains the indicators used in this paper to measure them. We show how these characteristics could be related to efficiency in the knowledge diffusion among the inventors within the clusters and suggest the possible impact on innovation creation in the cluster.

Collaboration characteristics in the subnetworks

As Table 4 shows, 20-47% of collaborative relations between pairs of inventors involve repetitive instances of collaboration. Inventors in Toronto, Montreal and Ottawa tend to pursue collaborative relations with the same partners much more often than inventors in Vancouver or Edmonton. As for the smaller clusters, in Kingston almost half of the collaborative ties of the local inventors include repetitive collaborative relationships, and the repetitiveness is also high in Calgary. The strongest collaboration link in the network, i.e. the most frequently repeated collaborative relation, concerns two inventors in Toronto. They repeated their collaboration 50 times, i.e. their joint research resulted in 50 patents. The maximum number of repeated collaborations is also relatively high for Montreal (29), but surprisingly low for the similarly-sized Ottawa (6) and somewhat smaller Vancouver (12). On average, the innovative activities of inventors in Toronto involve considerably more co-inventors who collaborate with each other more often than in any other nanotechnology cluster studied.

Table 4: Structural properties of the cluster-based subnetworks

Cluster *	TRT	MTL	OTT	VAN	EDM	QUE	KIN	CAL	Network
# of inventors	487	180	179	142	79	47	35	33	1968
COLLABORATION CHARACTERISTICS									
# of collaborating pairs	1295	201	218	199	112	53	36	41	4920
% of repeated collaborations	38%	36%	35%	20%	24%	21%	47%	41%	34%
Max # of repeated collaborations	50	29	6	12	6	3	4	8	50
FRAGMENTATION									
# of components	132	73	68	52	27	19	17	17	407
Size of the 1st largest component	155	21	23	21	15	6	5	8	336
Size of the 1st largest as % of all	32%	12%	13%	15%	19%	13%	14%	24%	17%
Ratio 2nd/1st largest	0,08	0,48	0,43	0,43	0,93	1,00	1,00	0,50	0,09
Average component size	3.69	2.47	2.63	2.73	2.93	2.47	2.06	1.94	4.84
Share of components with 50% of inventors	21%	34%	29%	31%	26%	47%	53%	35%	26%
Isolates as % of inventors	11%	19%	18%	18%	15%	17%	29%	30%	4%
STRUCTURAL COHESION									
Subnetwork density	0,011	0,012	0,014	0,020	0,036	0,049	0,061	0,078	0,003
Average degree	5,32	2,23	2,44	2,80	2,84	2,26	2,06	2,48	5,00
CENTRALIZATION OF SUBNETWORK									
Degree centralization	0,08	0,07	0,04	0,09	0,15	0,06	0,06	0,15	0,02
Betweenness centralization	0,009	0,005	0,007	0,013	0,020	0,008	0,005	0,000	0,006
CENTRALITY OF VERTICES									
Max degree centrality	42	15	9	16	14	5	4	7	54
Max closeness centrality	0,16	0,09	0,06	0,12	0,19	0,13	0,14	0,24	0,06
Max betweenness centrality	0,009	0,005	0,008	0,013	0,021	0,008	0,005	0,000	0,006
GEODESIC DISTANCES									
Subnetwork diameter	7	4	10	3	3	3	2	1	17
Avg distance (reachable vertices)	2,56	1,67	2,58	1,61	1,60	1,22	1,08	1,00	4,16
Max reach	154	20	22	20	14	5	4	7	335
CLIQUISHNESS									
Average egocentric density	0,54	0,49	0,56	0,64	0,59	0,52	0,50	0,45	0,76

* TRT	…Toronto	EDM	…Edmonton	WIN	…Winnipeg	QUE	…Quebec
MTL	…Montreal	CAL	…Calgary	KIN	…Kingston	HAL	…Halifax
VAN	…Vancouver	SAS	…Saskatoon	OTT	…Ottawa	SHE	…Sherbrooke

Fragmentation of the subnetworks

A component is defined as the maximal connected subnetwork (Wasserman and Faust, 1994). It is a part of the network which includes a maximum number of vertices which are all directly or indirectly connected by links. The *largest component* is found in the Toronto cluster and consists of 155 inventors, or around 32% of all the Toronto nanotechnology inventors. In contrast, the largest components of the other clusters are considerably smaller: in Montreal, Ottawa and Vancouver they comprise around 21-23 inventors, which represents only 12-15% of the cluster subnetwork size. As compared with Toronto, a much smaller number of inventors in these clusters are directly or indirectly interconnected and thus cannot exchange scientific knowledge as easily as in Toronto. The *second largest components* are of similar sizes for the main clusters. In the case of Toronto however, this implies that the second component is more than 10 times smaller than the largest component. In contrast, for the other three clusters the second largest components are around half the size of the largest ones and in Edmonton, they are almost of the same size. These cluster subnetworks are overall more fragmented than that of Toronto. In smaller clusters the larger components are in general of comparatively smaller sizes than in the larger clusters and the size of the second largest component is usually much more closer to the size of the first largest (in Kingston for instance, they even are of exactly the same size).

The *average component size* is fairly small for all the clusters. The Toronto subnetwork here stands out again: it includes components of a larger relative size: the mean number of interconnected inventors is 3.7. Moreover, half of the inventors form only around 20% of all the components, whereas this percentage is much larger for all the other clusters. Toronto also has the lowest ratio of inventors working without any collaborators within the same cluster (11.3%). The remaining clusters have on average a comparable numbers of connected inventors (around 2.5-2.9 inventors). The counts of *isolate vertices* are also comparable for the four larger clusters (15%-19% of all the vertices), but relatively high for the smaller clusters (e.g., Calgary or Kingston). In general, around 20% of inventors in the subnetworks do not have any collaborator in the cluster and work in geographical isolation.

Structural cohesion of the subnetworks

Structural cohesion refers to the degree to which vertices are connected among themselves. The most common measure of cohesion is the *density of a network,* which is the number of existing lines in the network expressed as a proportion of the maximum number of possible lines. Table 4 shows the subnetwork densities for each cluster. It is evident that for the networks of smaller sizes the density is higher and vice versa. Even though density is an indicator often used in social network analysis, it is more suitable to compare networks of the similar sizes, since density is inversely related to network size. De Nooy *et al.* (2005) explain that this is because the number of possible lines increases rapidly with the number of vertices, whereas the number of social ties, which each person can maintain is limited. We therefore measure the density by the average degree of a network. *Degree of a vertex* is the number of lines that are directly connected to the vertex (Wasserman and Faust, 1994). It represents the number of direct collaborators with whom an inventor cooperated on at least one patent. The more co-inventors of each inventor, the tighter is the network structure. The *average degree of a network* then denotes the average of the degrees of all vertices, and in fact it also shows the average number of co-inventors in each subnetwork, which we discussed earlier. The innovation subnetwork in the cluster of Toronto is by far the densest in Canadian nanotechnology. The inventors in Toronto have direct or indirect access to a larger amount of information and a greater number of inventors. Consequently the possibility for two inventors to get in touch through a chain of personal acquaintances is higher as well.

Centrality of vertices

The *centrality of a vertex* indicates whether the position of an individual inventor within the subnetwork is more central or more peripheral. Inventors that are more central have better access to information and better opportunities to spread information. We expect that inventors who occupy the most central positions in the subnetworks will be the most influential and probably the most prolific as well. We measure three indicators of vertex centrality: degree centrality, closeness centrality and betweenness centrality for all the inventors in our database. The simplest definition of centrality is the *degree centrality of a vertex*, which is in fact equal to the degree of the vertex defined above. Inventors in more central positions in the subnetwork are those directly connected to more inventors and thus have more sources of information at their disposal. The most connected inventor within his own cluster lives in Toronto (he has 42 co-inventors). The most central inventors from other clusters are much less connected: Vancouver's, Montreal's and Edmonton's most connected inventors have 14-16 direct collaborators and Ottawa's only 9. *Closeness centrality of a vertex* is the number of other vertices divided by the sum of all distances between the vertex and all others (de Nooy *et al.*, 2004). It measures the centrality of an inventor in terms of his closeness to other inventors, i.e., his ability to interact with the others and consequently the speed of his access to all the information in the subnetwork. Based on closeness centrality, there is a very central inventor in the small cluster of Calgary, but also in Edmonton and Toronto. Finally, *betweenness centrality of a vertex* is defined as the proportion of all shortest distances between pairs of other vertices that include this vertex (de Nooy *et al.*, 2004). An inventor is more central if a lot of shortest paths between pairs of other inventors in the subnetwork have to go through him. Betweenness centrality is therefore based on the inventor's importance to other inventors as an intermediary and it measures his control over the interactions between other inventors and thus over the flow of information in the subnetwork. Edmonton's most central inventor based on the closeness centrality indicator occupies the most central position if measured by betweenness centrality as well. In sum, Toronto benefits from several quite central inventors (surpassing others, particularly in degree centrality), but so does Edmonton, with its most central inventor enjoying high maximum centrality levels as well.

Centralization of the subnetworks

Contrary to centrality, which refers to the positions of individual inventors, centralization characterizes an entire network. A highly centralized network has a clear boundary between the center and the periphery. The center of a centralized network allows more efficient transmission of information, which consequently spreads fairly easily in highly centralized networks. A network is hence more centralized if the centralities of vertices vary substantially. The *Centralization of a network* is defined as the variation in the degree centrality of vertices, divided by the maximum degree variation which is possible in a network of the same size (de Nooy *et al.*, 2004). Similarly to centrality, there are three main measures of network centralization: degree centralization, closeness centralization and betweenness centralization. *Degree centralization of a network* is based on the variation in degree centrality of vertices in a network. The Edmonton and Calgary subnetworks show the highest degree centralization scores. Analogous to degree centralization, *closeness centralization of a network* is based on the variation in closeness centrality of vertices in the network. This however can be measured only in a connected network (i.e., where all vertices are directly or indirectly connected), as otherwise there are no paths between some vertices and thus it is impossible to compute the distances between them. Our subnetworks are not connected and therefore we cannot measure closeness centralization. Finally, *betweenness centralization of a network* is based on the variation in betweenness centrality of vertices in the network. Betweenness centrality can be computed even in unconnected networks. The results are also shown in Table 4. It is again Edmonton, which previously showed the highest maximal betweenness centralities of the vertices and now scores the highest in betweenness centralization of all the subnetworks as well.

Geodesic distances in the subnetworks

The shortest path between two vertices is referred to as geodesic. The *geodesic distance* is the length of a geodesic between them and depends on the number of intermediaries needed for an inventor to reach another inventor in the subnetwork. A short path length in innovation networks should improve knowledge production and knowledge diffusion (Cowan and Jonard, 2004; Fleming *et al*., 2004), since knowledge can reach the different parts of a network more quickly and spread rapidly among inventors. Moreover, as Cowan and Jonard (2004) suggest, a decreased path length will cause knowledge to degrade less by bringing new sources of ideas and perspectives from farthest parts of the network to the inventors.

The longest geodesic in a network (the longest shortest path) is called the *diameter of a network*. It quantifies how much apart are the two farthest vertices in a network and it is a rough indicator of the effectiveness of a network in connecting pairs of inventors. The largest diameter in our subnetworks is found in the Ottawa and Toronto clusters, where information from one inventor may need as many as 9 (6, respectively) intermediaries to reach another inventor. The exchange of information is much easier in Vancouver, Montreal, Edmonton and many other smaller clusters. In general, the diameters appear to be extremely long when compared to the overall size of the component. This suggests quite a low connectedness of our subnetworks. An indicator is the *average distance of a network* which denotes the average of all the distances of all the vertices in the subnetwork. In general, it is a more global measure of efficiency in communication, but here it shows similar results. On average, it takes a longer time to transfer knowledge in Ottawa and Toronto (1-2 intermediaries are needed), whereas the knowledge travels faster in Edmonton, Vancouver or Montreal, where it takes on average less than 1 intermediary for knowledge to be transferred anywhere in the cluster. Obviously, the geodesic distances are also lower in smaller clusters. Moreover, it should be taken into consideration that the distances are calculated only between reachable vertices (i.e., directly or indirectly connected), as the distance between two unconnected vertices is not defined (does not exist). This may bring a certain bias to our results, since any small or highly disconnected subnetwork should yield lower scores for geodesic distances. Therefore it is necessary to evaluate this measure more globally – while considering how many inventors could be reached within the cluster. The *reach of a vertex* is defined as the number of vertices that can be reached from this particular vertex. Table 4 shows the maximal reach for each subnetwork, i.e. the maximum number of reachable inventors within a subnetwork. Evidently, more inventors could be directly or indirectly reached in larger networks. In the Toronto subnetwork 154 inventors can reach each other, while in the Ottawa, Montreal and Vancouver cluster it is only 20-22 inventors who are connected among themselves and among whom knowledge can spread easily. The clusters with lower maximal reach are likely to be more disconnected and thus show lower scores of geodesic distances, whereas the clusters with the highest numbers of reachable vertices are more connected and should show higher geodesic distances. Toronto has a maximal reach many times over than that of other clusters, but the average shortest distance of the Toronto subnetwork is not considerably higher than that of the other clusters and in fact even slightly lower than that of the much smaller cluster of Ottawa. This is indicative of a network structure which enables more efficient knowledge diffusion.

Cliquishness in the subnetworks

Cliquishness is the property of a local network structure which refers to the likelihood that two vertices that are connected to a specific third vertex are also connected to one another. Cliquish networks have a tendency towards dense local neighbourhoods, in which individual inventors are better interconnected with each other. Such networks exhibit a high transmission capacity, since a great amount of information could be diffused rapidly (Burt, 2001). Moreover, a high degree of cliquishness in an innovation network supports friendship and trust-building, and hence facilitates collaboration between innovators. Uzzi and Spiro (2004) and Schilling and Phelps (2007) argue that a higher degree of cliquishness enhances system performance and knowledge diffusion. However, Cowan and Jonard (2003) point out the existence of negative effects of cliquishness stemming from the loss due to repetition, as the knowlegde exchanged in highly cliquish neighbourhoods is often redundant. Moreover, empirical findings of Fleming *et al.* (2006) confirm the negative impact of the higher degree of cliquishness in the network on innovative productivity. The role of a high degree of cliquishness in the innovation production is still not obvious and the optimal degree will apparently depend on a variety of factors.

In this paper, we measure the degree of local cliquishness for each vertex with egocentric density of a vertex, which is the fraction of all pairs of the immediate neighbours of a vertex that are also directly connected to each other, and then we calculate the *average egocentric density of a subnetwork.* The highest values for cliquishness are found in Vancouver, Edmonton, Ottawa and Toronto. The degree of cliquishness is quite high among the larger subnetworks, only Montreal shows much lower cliquishness. The subnetworks of the smaller sizes are less cliquish as well.

We can conclude that in order to enhance the efficiency of each network in terms of knowledge diffusion, the network should be cohesive (which means that inventors are closely interconnected), cliquish (which fosters trust and close collaboration), it should have a long reach within large components (which enables bringing fresh and non-redundant knowledge from distant locations) and it should have a centralized structure (which supports fast information transmission). As Table 4 shows, the closest to these properties are the subnetwork structures of Toronto, Edmonton and Vancouver. Toronto's is the densest network of the Canadian nanotechnology clusters, where researchers are better interconnected and knowledge can hence be diffused quite rapidly. It has on average the largest components and the lowest share of geographically isolated researchers of all the clusters. Despite the great mean size of the components, the path lengths are still only slightly higher than average. Information can thus spread through a great number of researchers in a timely manner. The Toronto subnetwork is however only moderately cliquish and centralized. In contrast, inventors from both Edmonton and Vancouver clusters benefit from fairly cliquish and rather centralized nanotechnology subnetworks, the structure which supports both the trust-building among the researchers and a more efficient transmission of information through the centrally located researchers. The larger-sized components with quite short geodesic distances make it easier to bring new information fast to a relatively high number of inventors in both clusters. As for the clusters of Montreal and Ottawa, we found that the structural properties of their intra-cluster subnetworks are not very supportive of efficient knowledge diffusion and innovation generation. Both subnetworks are quite sparse and neither very cliquish nor centralized. They consist of the components of rather small sizes, which explains the relatively short path lengths measured in the networks. Also, a high percentage of researchers in both clusters work in a geographical isolation. These characteristics suggest a great disconnectedness among the inventors in a cluster. Nonetheless, the structural network properties are quite diverse within the individual clusters and their exact role in the knowledge creation and innovation generation still remains to be determined.

4. Conclusions

The purpose of this work was to study social networks of inventors, in which co-inventorship of one or more nanotechnology patents registered at the USPTO represents a collaborative tie between two innovators. The innovation network constructed in this way revealed not only the main patterns of collaborative behaviour of Canadian nanotechnology inventors inside and outside clusters, but also allowed us to evaluate the network efficiency in knowledge diffusion and its role in the innovation creation.

The results show that more than 60% of the nanotechnology collaborative activity which involves Canadian inventors takes place within Canadian clusters. We found that inventors in Toronto, the cluster with the overwhelmingly most populous nanotechnology research community, tend to collaborate more than others within their own cluster, where inventors with a specific knowledge in the field are probably available and more easily accessible. On the other hand, inventors in smaller clusters usually have to look for collaborators possessing a particular expertise outside their clusters. Collaboration of inventors from distinct Canadian clusters accounts for only around 12% of all the collaborative ties. We have identified two inter-cluster collaborative patterns in Canadian nanotechnology innovation. *Eastern clusters* with local interests are the five nanotechnology clusters located in the eastern part of Canada (Toronto, Montreal, Ottawa, Quebec and Kingston). They seek cooperation ties within a relatively short distance from their own cluster and collaborate mainly between each other. *Western clusters* with eastern interests are the clusters situated in the western part of Canada (Vancouver, Edmonton and Calgary). They are characterized by inventors with a primary preference for innovation partners from the relatively distant Eastern clusters and a much lower interest in geographically more proximate collaborative relationships. Toronto's inventors are by far the most popular cooperation partners for Canadian nanotechnology researchers from other clusters or elsewhere in Canada. However, Canadian inventors who decide to pursue their joint nanotech research activities with inventors from outside their clusters quite frequently prefer searching for collaborative partnerships abroad. International ties account for around 27% of all collaborations. The most popular foreign collaboration partners for Canadian nanotechnology inventors reside south of the border, in the USA.

When we disregarded the geopolitical divisions and took into consideration only geographical distances, we observed that distance plays an important role when deciding on the partners for joint research projects in nanotechnology. An overwhelming preference of Canadian inventors is towards local and relatively proximate partnerships. Nonetheless, if the suitable collaborators are not found within 600 km, the importance of the geographical factor significantly decreases, since in this case the inventors quite often opt for very distant or overseas cooperation. Other factors (nanotechnology specialization, particular expertise, available facilities, previous acquaintance etc.) then become more prominent in explaining the inventors' choices.

Finally we examined the structural network properties of each cluster and related them to the efficiency of each subnetwork in knowledge diffusion and innovation creation. We observed that the network should be cohesive (which means that the inventors are closely interconnected), clustered (which fosters trust and close collaboration), it should have a long reach within large components (which enables bringing fresh and non-redundant knowledge from distant locations) and it should have a centralized structure (which supports fast information transmission). The structural network properties are quite often diverse within the individual clusters and their exact role in knowledge creation and innovation generation still remains to be determined.

This paper represents a step towards the understanding of the influence of knowledge networks on the innovative activities of inventors located within high technology clusters. The question as to the exact role played by networks and their importance in the chain of knowledge creation however requires the construction of a formal model that would globally represent knowledge creation. In this paper, we have set the bases for the realisation of this model. We have collected relevant information about nanotechnology collaboration networks in Canada, which will be the foundation of our full model. Another research avenue which is currently being explored involves the study of the network of Canadian nanotechnology scientists, who are the authors or co-authors of the scientific articles. This will enable us to investigate the influence of the nature and the structure of the networks of various innovators (i.e. inventors and scientists) on the propensity to innovate of firms in clusters. We intend to merge the two databases to gain a full picture of the innovation production in Canadian nanotechnology.

References

Allen, R.C. (1983). Collective invention. Journal of Economic Behaviour and Organization, 4, 1-24.

Balconi, M., Breschi, S., and Lissoni, F. (2004). Networks of inventors and the role of academia: An exploration of Italian patent data. Research Policy, 33, 127-145.

Baptista, R. and Swann, P. (1998). Do firms in clusters innovate more? *Research Policy*, 27, 525-540.

Beaucage, J-S. and Beaudry, C. (2006). The Importance of Knowledge Networks within Canadian Biotechnology Clusters. International Schumpeter Conference, Sophia-Antipolis

Beaudry and Swann (2008 forthcoming) Firm-level growth in industrial clusters: a bird's eye view of the United Kingdom, Small Business Economics.

Beaudry, C. (2001). Entry, growth and patenting in industrial clusters. International Journal of Economics of Business, 8, 3, 405-436.

Beaudry, C. and Breschi, S. (2003). Are firms in clusters really more innovative? Economics of Innovation and New Technology, 12, 4, 325-342

Breschi, S. and Lissoni, F. (2003). Mobility and social networks: localized knowledge spillovres revisited. CESPRI Working Papers, 142.

Breschi, S. and Lissoni, F. (2004). Knowledge networks from patent data: Methodological issues and research targets. CESPRI Working Papers, 150.

Burt, R. (2001). Bandwidth and echo: Trust, information, and gossip in social networks . In: A. Casella and J.E. Rauch (Eds.), Networks and Markets: Contributions from Economics and Sociology New York: Russel Sage Foundation.

Cantner, U. and Graf, H. (2006). The network of innovators in Jena: An application of social network analysis. Research Policy, 35, 463-480.

Cockburn, I.M. and Henderson, R.M. (1998). Absorptive capacity, coauthoring behavior, and the organization of research in drug discovery. The Journal of Industrial Economics, 46(2), 157-182.

Cowan, R. and Jonard, N. (2003). The dynamics of collective invention. Journal of Economic Behaviour and Organization, 52, 513-532.

Cowan, R. and Jonard, N. (2004). Network structure and the diffusion of knowledge. Journal of Economic Dynamics and Control, 28, 1557-1575.

Cowan, R., Jonard, N. and Ozman, M. (2004). Knowledge dynamics in a network industry. Technological Forecasting and Social Change, 71, 469-484

Cowan, R., Jonard, N., and Zimmermann, J.-B. (2007). Bilateral collaboration and the emergence of innovation networks. Management Science, 53, 7, 1051-1067

CREA. (2005). Creative capabilities and the promotion of highly innovative research in Europe and the United States, European Commission, Project Reference 511889 (NEST).

Dahl, M.S. and Pedersen, C.O.R. (2004). Knowledge flows through informal contacts in idustrial clusters: myth or reality? Research Policy, 33, 1673-1686.

de Nooy, W., Mrvar, A. and Batagelj, A. (2005). Exploratory Social Network Analysis with Pajek. Cambridge: Cambridge University Press

Ducor, P. (2000). Intellectual property: Coauthorship and coinventorship. Science, 289(5481), 873-875.

Ejermo, O. and Karlsson, C. (2006). Interregional inventor networks as studied by patent coinventorships. Research Policy, 35, 412-430.

Fleming, L., King, C.IV., and Juda, A. (2006). Small worlds and innovation. SSRN Working Papers.

Gauvin, S. (1995). Networks of innovators: Evidence from Canadian patents. Group Decision and Negotiation, 4, 411-428.

Gittelman, M. (2006). Does Geography Matter for Science-Based Firms? Epistemic Communities and the Geography of Research and Patenting in Biotechnology. DRUID Summer Conference on Knowledge, Innovation and Competitiveness: Dynamics of Firms, Networks, Regions and Institutions, Copenhagen, Denmark.

Krebs, Valdis. (2006). Social network analysis. Available on-line: http://www.orgnet.com/sna.html

Lamoreaux, N.R. and Sokoloff, K.I. (1997). Location and technological change in the American glass industry during the late nineteenth and early twentieth century. NBER Working Papers, 5938.

Mariani, M. (2000). Networks of inventors in the chemical industry. MERIT Research Memorandum.

Morone, P. and Taylor, R. (2004). Knowledge diffusion dynamics and network properties of face-to-face interactions. Journal of Evolutionary Economics, 14, 327-351.

Newman, M.E.J. (2001a). Scientific collaboration networks. I. Network construction and fundamental results. Physical Review, 64, 016131.

Newman, M.E.J. (2001b). Scientific collaboration networks. II. Shortest paths, weighted networks, and centrality. Physical Review, 64, 016131.

Newman, M.E.J. (2001c). Clustering and preferential attachment in growing networks. Physical Review, 64, 025102.

Newman, M.E.J. (2001d). The structure of scientific collaboration networks. Proceedings of National Academy of Sciences, 98(2), 404-409.

Newman, M.E.J., Watts, D.J., and Strogatz, S.H. (2002). Random graph models of social networks. Proceedings of the National Academy of Sciences, 99, 2566-2572.

Putsch, F. (2006). Analysis and modeling of science collaboration networks. Working Paper.

Saxenian, A. (1994). Regional Advantage: Culture and Competition in Silicon Valley and Route 128. Cambridge, MA: Harvard University Press.

Schilling, M.A. and Phelps, C.C. (2007). The impact of large-scale network structure on firm innovation. Management Science, 53, 7, 1113-1126

Schrader, S. (1991). Informal technology transfer between firms: Cooperation through information trading. Research Policy, 20, 153-170.

Singh, J. (2005). Collaborative networks as determinants of knowledge diffusion. Management Science, 51(5), 756-770.

Uzzi, B. and Spiro, J. (2005). Collaboration and creativity: The small world problem. American Journal of Sociology, 111 (2), 447-504.

von Hippel, E. (1987). Cooperation between rivals: Informal know-how trading. Research Policy, 16, 291-302.

Wasserman, S. and Faust, K. (1994). Social network analysis. Cambridge: Cambridge University Press.