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IMPEDIMENTS AND FACILITATORS OF TECHNOLOGY ADOPTION AND DIFFUSION: A LITERATURE SURVEY OF THE LAST 10 YEARS

Johannes Van Biesebroeck, University of Toronto

Working Paper 2007-06

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Abstract

With increasing globalization of markets, Canadian firms are facing fierce and growing competition. To remain internationally competitive, Canadian firms are expected to produce high-quality, customized goods quickly and at reasonable cost. Adoption of advanced technologies is a crucial ingredient to meet this challenge. Adoption and diffusion of advanced technologies or work practices are the outcomes of deliberate processes. Heterogeneity in incentives, firm capabilities, and government interventions lead to important variations in technology use across industries and firms. This paper provides a review, summary, and critical evaluation of several distinct literatures that identify impediments and facilitators to the adoption and diffusion of advanced technology. The paper starts by discussing the link between technology use and productivity and proceeds with an overview of the different sources of information that researchers have used to learn about the technology adoption process. The remainder and bulk of the paper is devoted to surveying evidence on the importance of a variety of impediments and facilitators drawing on studies from all countries, industries, and technologies. We point, in particular, to the importance of information. In the inherently uncertain process of adopting new technologies, the government can play an important role facilitating the sharing or creation of information. For example, governments can provide firms with information about new technologies, identify complementarities or quantify expected benefits. Governments can also put policies in place to help firms use existing information more effectively, such as providing expert information on available technological options.

Key words: technology adoption; government policy; innovation; productivity

Résumé

En raison de la mondialisation croissante des marchés, les entreprises canadiennes doivent soutenir une concurrence vive et galopante. Pour maintenir leur compétitivité internationale, les entreprises canadiennes doivent produire rapidement et à un coût raisonnable des produits sur mesure et de grande qualité. Les technologies de pointe sont essentielles à cet égard. L’adoption et la diffusion des technologies de pointe ou de pratiques de travail d’avant-garde résultent de processus délibérés. La diversité des incitatifs, les capacités des entreprises et les interventions gouvernementales se traduisent par d’importants écarts dans l’utilisation des technologies entre industries et entre entreprises. Le présent document examine, résume et évalue de façon critique plusieurs ouvrages qui traitent des facteurs qui empêchent et ceux qui facilitent l’adoption et la diffusion des nouvelles technologies. Le document débute par un examen du lien qui existe entre la technologie et la productivité et passe ensuite en revue diverses sources d’information auxquelles les chercheurs ont eu recours pour comprendre le processus d’adoption des technologies. La partie qui suit et qui forme le gros du document consiste en un tour d’horizon des preuves de l’importance de toute une gamme d’obstacles et d’agents de facilitation définis à la lumière d’études émanant d’industries, de technologies et de pays divers. Nous insistons plus particulièrement sur l’importance de l’information. Dans ce processus d’adoption de technologies, dont l’incertitude est inhérente, le gouvernement peut tenir un rôle de premier plan en facilitant la mise en commun ou la création de l’information. Par exemple, les gouvernements peuvent offrir aux entreprises de l’information sur les nouvelles technologies, définir des complémentarités ou chiffrer les avantages attendus. Ils peuvent aussi mettre en œuvre des politiques afin d’aider les entreprises à utiliser plus efficacement l’information, notamment en fournissant de l’information pertinente sur les options disponibles en matière de technologie.

Mots clés : adoption de technologies, politique gouvernementale, innovation, productivité

Executive summary

With increasing globalization of markets, Canadian firms are facing fierce and growing competition. To remain internationally competitive, on the export market or competing with imports at home, Canadian firms are expected to produce high-quality, customized goods quickly and at reasonable cost. Adoption of advanced technologies is a crucial ingredient to meet this challenge. Adoption and diffusion of advanced technologies or work practices are the outcomes of deliberate processes. Heterogeneity in incentives, firm capabilities, and government interventions lead to important variations in technology use across industries and firms.

The main objective of the paper is to provide a review, summary, and critical evaluation of several distinct literatures that identify impediments and facilitators to the adoption and diffusion of advanced technology. The paper starts by discussing the link between technology use and productivity and proceeds with an overview of the different sources of information that researchers have used to learn about the technology adoption process. The remainder and bulk of the paper is devoted to surveying evidence on the importance of a variety of impediments and facilitators drawing on studies from all countries, industries, and technologies. Two tables in the Appendix summarize the most important studies.

The most important output of the survey is to discern the role governments can play by removing obstacles, altering incentives, enhancing capabilities, and putting in place appropriate infrastructure. From a policy perspective, it is useful to separate the impediments into two categories – those that are external to the firm and those that coincide with specific firm characteristics.

In the former group we place (i) the competitiveness of the industry, (ii) uncertainty surrounding the technology, (iii) regulatory environment, (iv) geographic proximity between adopters, and (v) complementarities between aspects of a technology. Some of these, like proximity or uncertainty are more or less beyond government control. However, incomplete information on benefits as well as costs is a major concern for adopters. Governments can aid participants to make maximum use of the available information or facilitate information sharing between potential adopters. In some instances a central planner can find it optimal to make investments to clear up uncertainty, which could be beyond a single agent. The regulatory environment and to some extent the competitiveness in an industry can certainly be influenced by government policy, but their effects on the likelihood or speed of adoption are not clear-cut. It is not even the case that greater competitiveness or less regulation will lead to more efficient decision making, be it more or less adoption. Finally, complementarities between technologies are again beyond government control, but these again provide a role for governments to act as information brokers. As a central authority it is more likely to touch a variety of aspects of a technology facilitating the identification of complementarities and allowing for the possibility to remove minor obstacles in, at first sight, unrelated dimensions.

The most important firm characteristics that have been shown to correlate with technology use and adoption are (i) foreign ownership or interactions with foreign firms more generally, (ii) size, (iii) prior experience with the technology, (iv) internal organization, (v) perceptions of benefits associated with adoption, (vi) learning from other adopters, (vii) employee skill level, (viii) lack of financing, and (ix) lack of information. As with the external factors, we again stress the role governments can play facilitating the spread and creation of information. Perception of benefits, learning from prior adoption, and perceived lack of information are all factors that governments can help to overcome. Most of the other firm-specific obstacles to adoption are less amenable to government intervention. For example, small and domestically-oriented firms are demonstrably less prone to adopt new technologies, perhaps due to informational disadvantages or fixed costs inherent to the adoption process. However, policies that lower the adoption costs for such firms are unlikely to be successful, as the size distribution and export status of firms are not randomly assigned. It is well documented that more productive firms grow more quickly, enter export markets and are significantly more likely to survive. Unless there is a clear market failure, it is unlikely that intervening in one dimension where a firm is lagging – its use of advanced technology – will increase its chances of future success. Many firms cite lack of financing or low employee skill level as reasons for postponing adoption, but these are as much indications of inefficient use of financial resources and an inability to retain skilled workers as real constraints. We will document a number of instances where the removal of such perceived constraints has had very little impact.

We conclude that the most promising role for government to influence technology adoption is to act as information broker. A central agency can *provide firms with information* about the new technologies, identify complementarities or quantify expected benefits. An independent actor can summarize *information about the environment*: communicate experiences of other firms with the new technology or taking actions to reduce uncertainty about benefits. Organizing these activities in a government agency or department has at least two advantages over government funding for an industry association to carry out the same tasks: it will be easier to incorporate experiences of other industries and as a non-competing entity distrust is likely to be lessened. Finally, governments can also put policies in place to *help firms use existing information* more effectively: provide expert information on the available technological options, provide information on internal reorganizations that have proven to be necessary for successful adoption, or identify foreign information sources of new technologies.

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1. Introduction

With increasing globalization of markets, Canadian firms are facing fierce and growing competition. To remain internationally competitive, on the export market or competing with imports at home, Canadian firms are expected to produce high-quality, customized goods quickly and at reasonable cost. Adoption of advanced technologies is a crucial ingredient to meet this challenge. Governments the world over are tailoring industrial policies to induce firms to make appropriate investments. Given that many technologies are subject to externalities, e.g. because they lead to spillovers to other firms or they require complementary investments in training which adds to the general human capital of the workforce, it is possible that profit maximizing firms will under-invest in new technologies.

On a number of technology indicators, Canada is lagging the U.S. and many other advanced economies.[1] This can be observed most clearly from the inputs and investments that go into knowledge creation. For example, in 2001 research and development (R&D) expenditure as a percentage of GDP in Canada was 2.03%, below the OECD average of 2.28% and only 13th in the group of OECD countries. The OECD estimates that only 30% of the gap between Canada and the U.S., which spends 2.73% of its GDP on R&D, is the result of a different industry composition, the remaining being a lower average R&D intensity within each industry. Graduation rates for tertiary education and the number of Ph.D. graduates per population (in 2000) are significantly lower than in the U.S., the U.K., or France. Investment in machinery and equipment as a percentage of GDP was lower in Canada than in any other G-7 country for most of the last two decades. Moreover, by 2001 purchases of foreign intellectual property had declined to levels much below Germany's, Japan's, or the U.K.'s. In addition, patenting rates, the best available measure of domestically created knowledge, are far lower in Canada than in the U.S. and many of the most research intensive European countries. For 2004, the World Economic Forum ranks

[1] R&D ratios and information on patenting and purchases of foreign intellectual property are calculated from statistics in the OECD's *Main Science and Technology Indicators, 2004/2.* Education attainments come from OECD, *Education at a Glance, 2002* and Cervantes (2004), "Trends in Supply and Demand for Human Resources in Science and Technology," *OECD Science and Technology Policy Division*. Information on investment in machinery and equipment is taken from OECD *National Accounts*. The World Economic Forum publishes its rankings of countries in the *Global Competitiveness Report.*

Canada only 27th in the world in terms of "propensity to compete on the basis of unique products and processes."

In this paper we will review some of the evidence indicating that these input differences translate in an output gap in innovation and lower technological sophistication.[2] Using indicators of technology adoption, technology usage, and technology creation, Canada is lagging many of the G-7 countries and several of the smaller OECD countries. This raises two questions. Does it matter? And if it does, what can be done about it? Most of the evidence points to a clear link between technology adoption and use and cross-country differences in productivity.[3] At a more disaggregate level, firms that use more advanced technologies also tend to have higher productivity. The endogenous growth literature even conjectures a relationship between the *level* of knowledge and the *rate of growth*. Evidence for such a channel has been found, but is not overwhelming.

This naturally leads to the question of what governments can do to remedy this situation. Adoption and diffusion of advanced technologies or work practices are the outcomes of deliberate processes. Heterogeneity in incentives, firm capabilities, and government interventions lead to important variations in technology use across industries and firms. From this variation it is possible to learn the factors that stimulate or inhibit adoption of new technologies. We first introduce different literatures that have exploited different sources of information to document and gain insights into the technology adoption process. Surveying these distinct literatures we are able to identify a number of factors that impede or facilitate the adoption and diffusion process. When discussing these factors, particular attention will be paid to the role governments can play by removing obstacles, altering incentives, enhancing capabilities, and putting in place appropriate infrastructure.

The remainder of the paper is organized as follows. Section 2 contains a discussion of the empirically documented link between technology and productivity at the country and firm level and discusses the different channels available to a country to incorporate best-practice

[2] Detailed econometrical evidence of such a link at the firm level is documented in Janz and Peters (2002). They find that skill of employees is particularly important in translating innovation expenditures into sales of innovative products.

[3] Parente and Prescott (2002) provide extensive examples how cross-country differences in income levels and productivity are related to technological differences. Comin and Hobijn (2004) provide more detailed and systematic evidence about the spread of technologies and productivity differences.

foreign knowledge into their economy. In Section 3, we survey the different sources of evidence used in the literature to learn about technology adoption and diffusion. The findings on impediments and facilitators that have been established in these various literatures are surveyed in Section 4. We first provide a general overview of and then focus in detail on two important exogenous and two important endogenous impediments. We also zoom in on two widely-studied technologies and we single out two industries to provide details on the exact way in which various impediments can have an impact. Finally, in Section 5 policy lessons are summarized. At each point, we will compare the international findings with Canadian evidence, where available.

2. Technology and productivity

While we are not interested in technology for its own sake, a clear link has been established between productivity and innovation or the use and adoption of advanced technology. Evidence from a cross section of countries on the link between firm-level innovation and aggregate productivity growth is in Lööf and Heshmati (2003). Gong and Keller (2003) discuss the link between relative income levels across countries and international technology diffusion. For Canada, the relationship between productivity growth and technological change is explored in Globerman (2002) and between productivity growth and innovation in Rao *et al.* (2002).[4]

For a more skeptical view, see Carlaw and Lipsey (2003). They argue that the relationship between technology and total factor productivity (TFP), a popular method to estimate productivity, is more tenuous. They argue that the literature too easily equates TFP with technology, while the direct link only exists under very special (and restrictive) circumstances.

[4] Baldwin and Diverty (1995) investigate at the plant level whether technology adoption increased productivity in the 1980s. Baldwin, Rama, and Sabourin (1999) and Baldwin and Sabourin (2002) perform a similar analysis for the 1990s with additional attention paid to information and communications technology and market share transfers.

Clearly, many new technologies and knowledge do not come about exogenously, but are man-made, Endogenous growth models in the spirit of Romer (1990)[5] indicate how profit maximizing firms will engage in innovative activities because they confer market power, at least temporarily. Tests of this model, using country or industry-level data, have generally not been supportive. Using time series variation, the model predicts long-lasting effects of the level of certain economic variables (proxies for knowledge) on growth rates. In reality, increases in R&D or human capital (engineers and scientists in the workforce) have not lead to higher growth rates; see for example Jones (1995). Gong, Greiner, and Semmler (2004) incorporate decreasing opportunities for technological innovations over time in the model, which reduces the return of the economic variables over time, and they do find support for the model using time series for the U.S. and Germany.

Cross-sectional studies, exploiting variation across countries, have also failed by and large; see the survey by Durlauf and Quah (1999). These studies have been criticized because countries at different stage of development are lumped together and preference and technology parameters are assumed to be constant across country and over time.

Much of the growth literature focuses on variables that are constant within a country, such as institutional quality, the legal system, educational attainment, inequality, etc. In this survey we are interested in identifying variables that explain variation (in technology adoption) across firms. Ehrlich *et al.* (1994) introduced a useful extension of the endogenous growth model to explain cross-firm differences in productivity growth. Their model has been used extensively to study the effect of ownership or evaluate the impact of privatization on firm performance. Van Biesebroeck (2003b) studies which other variables tend to be robustly associated with high productivity growth using two datasets on firms in Colombia and Zimbabwe. Most pertinent for the current discussion, he finds that frequent investments in physical capital are strongly related to productivity growth. Moreover, Zimbabwean firms that report adopting new technologies improve productivity at a 20% faster rate than other firms (the same variable is not observed in Colombia). Also notable is

[5] Romer's seminal paper has spawned a whole literature. A survey of this literature is beyond this paper and we refer the interested reader to the survey by Durlauf and Quah (1999) for the empirical literature testing the endogenous growth models.

that paying royalties is not associated with faster productivity growth, at least not for the sample of Colombian textile firms studied.

This leads to the more general question, especially pertinent to the study of technology adoption: Where does technology come from? For the majority of firms and countries, the technology used falls far short of worldwide best practice. As a result, diffusion of technology from more advanced countries is a prime channel for knowledge acquisition for all countries. Keller (2004) surveys the vast literature on international diffusion of knowledge, mostly taking countries as the unit of analysis. Among the most widely documented channels is international trade, FDI, licensing, and patents. We will briefly discuss each channel and provide references to papers that survey the literature more in-depth or provide a state of the art application.

International trade is a first channel that allows countries to import advanced technologies. At the aggregate level, the evidence is rather strong. One of the earliest papers was Coe and Helpman (1995) and Schiff and Wang (2006) have a recent contribution that provides up-to-date links to the literature. These studies have documented a link between R&D outlays of countries' trading partners and their own total factor productivity growth. The paper by Schiff and Wang (2006) allows for indirect effects, such as an effect of R&D by your trading partners' own trading partners. Brechner *et al.* (1996) provides evidence for very strong R&D spillovers between the U.S. and Canada. Unfortunately, they do not examine how the spillovers come about: through trade, FDI, or other links. For Canada, the effect is strong enough to lead to convergence in growth rates with the U.S. even though Canadian R&D expenditures are much lower.

While the aggregate evidence is quite strong, the same cannot be said about the plant or firm-level evidence. Several early studies attributed the observed correlation between productivity and export status entirely to self-selection of the highest productivity firms into the export market.[6] While this self-selection is clearly driving at least some of the correlation, a growing number of studies has now also found the reverse effect: learning-

[6] The literature studying the relationship between exporting and productivity is much more developed than studies that look at a relationship between importing of foreign inputs and productivity. Two important studies looking at the effect of importing are Kasahara and Rodrigue (2005), which looks at imported intermediate inputs, while Yasar and Morrison-Paul (2005) look at imported capital goods, in addition to export status and foreign ownership.

by-exporting. Baldwin and Gu (2003) provides such evidence for Canadian manufacturing. Lopez (2005) surveys and compares both the macro and micro literatures.

A second channel is FDI. One of the most influential studies in this area, Aitken and Harrison (1999), uses panel data on Venezuelan plants and finds that foreign equity participation is positively correlated with plant-level productivity. However, this finding is only robust for small enterprises. Grether (1999) analyses the determinants of technological diffusion in Mexican manufacturing. He finds that foreign capital has a positive effect on productivity efficiency at the plant level but, contrary to cross-industry studies, it does not lead to significant spillovers at the sector level. Braconier, Ekholm, and Knarvik (2001) utilize firm-level as well as industry-level data for Swedish manufacturing to determine whether inward and outward foreign direct investment work as channels for international R&D spillovers. They find no significant evidence of FDI-related R&D spillovers. Haskel, Pereira and Slaughter (2002) do not find such effects either using a plant-level panel covering U.K. manufacturing from 1973 to 1992: the effect of foreign-affiliate share of activity in a plant's region has only insignificant effects on a plant's TFP. In contrast, Barrel and Pain (1999) find empirical evidence for significant spillovers from inward investment on technological progress in the U.K., West Germany, France and the Netherlands. In the Canadian context, the proximity and close integration with the U.S. economy makes it even possible to obtain indirect benefits from R&D spillovers that happen in the U.S. Bernstein (2000) illustrates that by investing in communications infrastructure the Canadian economy benefits from U.S. R&D.

Jaffe, Trajtenberg, Fogarty (2000) use survey data from inventors to argue that patent citations are noisy signals of direct communication between inventors. Duguet and MacGarvie (2005) provide additional evidence on the usefulness of patent citations to track knowledge flows. These studies provide direct evidence that earlier patents help firms to develop new knowledge, which in turn gets embodied in patents and will have further influence down the line. MacGarvie (2006) uses patent citations to document that French importers filing for patents report the influence of foreign technology in their patent applications. Exporting, in contrast, is not significantly associated with citations to foreign patents. Her results are even robust after controlling for foreign ownership and joint ventures or alliances.

Evidence on the importance of patents and intellectual property rights more generally for Canada can be found in Putnam (2005). Chapter 9 by Walter G. Park provides evidence that strengthening Canadian patent rights would significantly increase long term productivity growth. Chapter 10 by Rafiquzzaman and Mahmud indicate that Canada's patenting rate in the U.S. has increased substantially in recent years. While no systematic information exists on cross-country patent citation patterns, firms from many countries – and especially Canadian firms – are increasingly taking advantage of the U.S. system of intellectual property protection and filing for U.S. patents early on. Given the large spillovers that have been estimated between U.S. patents, it is likely that this channel of technological information is increasing in importance for Canada.

Finally, licensing of foreign technology allows a country to acquire useful knowledge directly from the inventors. Branstetter, Fishman, and Foley (2006) provide evidence of such a channel at work through the affiliates of U.S. multinationals. However, focusing only on the growth rate of productivity, Van Biesebroeck (2003b) finds that Colombian textile plants that paid royalties had on average a significantly lower productivity growth rate.

While knowledge often comes from more advanced countries, technology can also come from R&D activities in nearby firms. Wieser (2005) surveys some of the firm-level evidence on spillovers from R&D. A variety of methods have been used to investigate the empirical relationship between R&D spending and the productivity of firms. The most widely employed frameworks are the production function and the associated productivity framework. In these settings, productivity growth is related to expenditures on R&D, and an attempt is made to estimate statistically the part of productivity growth that can be attributed to R&D activities. A large number of studies find a large and significant impact of R&D on average firm performance. However, the estimated returns vary considerably between the different studies due to differences in the samples, but also the econometric models, as well as methodological and conceptual approaches tend to vary widely. A meta-analysis on the studies surveyed reveals that the estimated rates of return do not significantly differ between countries, whereas the estimated elasticities do. Furthermore, the estimated elasticities are significantly higher in the 1980s and consistently higher in the

1990s compared with the 1970s. Hence, contrary to a widely held belief, there is no convincing evidence of an exhaustion of R&D opportunities in the last two decades

After documenting the many-faceted link between technology and productivity, we now turn to the different channels that researchers have relied on to learn about technology use in the economy and technology transfers between firms.

3. Evidence on technology adoption and spillovers

The most prominent approaches to studying the patterns and determinants of technology adoption and diffusion domestically or internationally include (i) firm surveys, (ii) patent citations, and (iii) the construction of specific technology use indicators, often limited to one industry. We survey all three in this section.

3.1. Technology adoption surveys

The first approach, technology adoption surveys at the plant or firm level, provides a direct measure of technology use. Statistical agencies in several countries conduct large scale surveys that ask questions about technologies that firms use and when they adopted them. In several of the surveys firms are asked to indicate which technologies that are explicitly listed they use, since when, and what the impact has been. Such surveys are organized by governmental agencies in several countries: Canada, USA, European Union (EU), Switzerland.[7]

Researchers have used them to learn about the relationship between innovation and several other variables, but unemployment[8], and productivity[9] have been particularly popular research subjects.

[7] For Canada, the surveys are organized by Statcan. Information on "The Survey of Innovation", which asks general questions about innovation practices in various aspects of a firms operation (not limited to production activities), can be found here:
http://www.statcan.ca/cgi-bin/imdb/p2SV.pl?Function=getSurvey&SDDS=4223&lang=en&db=IMDB
This site contains a copy of the actual questionnaire and discusses the sampling frame. Similar information for "The Survey of Advanced Technology in Canadian Manufacturing" can be found on the following web site: http://www.statcan.ca/cgi-bin/imdb/p2SV.pl?Function=getSurvey&SDDS=4223&lang=en&db=IMDB

[8] See studies by Harrison, Jaumandreu, Mairesse and Peters (2005), Jaumandreu (2003), Peters (2004), and Garcia, Jaumandreu, and Rodriguez (2002).

[9] See for example Janz, Lööf, and Peters (2003) for the E.U. and for Canada see Baldwin, Diverty and Sabourin (1995) for the 1980s and Baldwin and Sabourin (2002) cover the Canadian evidence for the 1990s.

Results from the surveys of the third round of the Community Innovation Survey (CIS3) for France, Spain, Germany, and the United Kingdom, four of the five largest EU countries, have been harmonized by researchers in each of the respective countries and are now used to study several issues comparing the different countries. Lucking (2005) discusses the E.U. survey and compares responses directly, with a particular focus on the adoption of advanced technologies. Abramovsky, Jaumandreu, Kremp, and Peters (2004) compare technology use for firms in each of the four countries in greater detail. Griffith, Huergo, Mairesse, and Peters (2005) study the relationship between innovation and productivity, again comparing patterns for the different countries.[10]

Statistics Canada has been very active in collecting information on technology adoption.[11] In addition, several researchers at Statistics Canada have been active in the literature analyzing the economic effects; a number of working papers describe the surveys and analyze adoption rates.[12] Baldwin and Sabourin (1997, 1998) compare Canadian adoption rates with the U.S. They find that among large plants adoption rates are similar for the two countries, but that small Canadian plants lag behind. Similarly, conditioning on the plant manager's subjective perception of competitiveness, there is no difference between Canadian and U.S. adoption rates. Finally, they find that Canadian plant managers worry more about the size of the market when contemplating adoption.

These types of surveys are the most appropriate source of information to study the speed of diffusion of existing knowledge, as embedded in capital equipment or management practices, see Baldwin, Sabourin, and Rafiquzzaman (1996) for Canada and Kremp and Mairesse (2004) for France. The latter use results from the French 1998-2000 Community

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[10] These papers, and many more, can be downloaded from the following web site: http://www.eco.uc3m.es/IEEF/documentpapers.html

[11] Statistics Canada occasionally conducts two surveys (sometimes jointly) that question firms on their technology use. The Survey of Advanced Technologies asks firms to indicate which technologies on a list they use currently or plan to use in the future. The Innovation Surveys asks firms more generally whether they have engaged in process or product innovations and what impact these had. The former have been conducted in 1989, 1993, and 1998; the latter surveyed the manufacturing sector for the last time in 1999. Similar questions as in the Innovation Surveys (and many more) are also posed to a smaller set of firms in the annual Workplace and Employee Survey (WES).

[12] Results on adoption rates from the three advanced technology surveys are described in Baldwin and Diverty (1995), Baldwin and Sabourin (1995), and Sabourin and Beckstead (1999). Linking plants that answered more than one survey over time, Baldwin, Rama, and Sabourin (1999) study the growth rate in technology adoption over the 1990s.

Innovation Survey which includes questions on the use of four knowledge management policies.

The rich cross-sectional variation allows one to focus on differences between firms and industries in terms of incentives, opportunities and absorptive capacity for new technologies. Examples of studies using similar survey data for other countries include Arvanitis and Hollenstein (2001) for Switzerland, Bartolini and Baussola (2001) for Italy, Dunne (1991) for the U.S. and Gourlay and Pentecost (2002) for the U.K. Particular attention is paid to technologies that increase flexibility in Faria, Fenn and Bruce (2003) and to the financial sector in Hannan and McDowell (1984).

A drawback of the survey methodology is that results are only available for a subset of the innovating firms, i.e. those that are (randomly) included in the survey. Given that most innovative activities take place in large enterprises, all surveys use stratified sampling to weigh the sample towards larger firms. In most cases weights are provided such that results can be obtained that are representative for the entire economy. A few examples exists where small and medium enterprises are singled out, see some limited evidence for the U.K. in Fu and Yang (2003) and for Information and Communication technologies (ICT) in Canada in Mallett (2001). Only rarely is information available in several years, which is required to study changes over time – the previously discussed European Commission and the Canadian surveys are notable exceptions here.

3.2. Patent citations

The second approach to measure technology development and also technology use is to track patent citations. Firms that patent a new technology will refer in their patent application to the existing knowledge, the 'prior art', as embodied in existing patents. These citations can be used to investigate how knowledge flows through the economy. This type of information is, by construction, available for all countries, it can potentially cover a long time period and refers, in principle, to the universe of innovating firms. Patent citations can be straightforwardly used to track international technology spillovers and they have also been used to study how existing knowledge and technology contributes to the creation of new knowledge.

Hu and Jaffe (2003) study knowledge transfers directly, using information from Korea, Japan, and the U.S. MacGarvie (2006) measures the effect of technology diffusion through international trade using patent citation information. A good overview of the evidence on Canadian innovation from patent data can be found in Trajtenberg (2002).

Patent counts have been used to study a variety of topics, including establishing a direct link between the level of technology and productivity. Johnson and Evenson (1997) document for Canada the clear link between innovative activities and inventions, as recorded by patenting. Fu and Yang (2003) compare patenting and R&D expenditure in the U.K, the U.S., and the E.U. Acosta and Coronado (2003) use citations of scientific sources in patent applications to study the interaction of science and the development and commercialization of new technologies.

Jaffe, Fogarty and Banks (1997) explore the commercialization of government-generated technology by analyzing patents awarded to the U.S. government and the citations to those patents from subsequent patents. Their findings are consistent with spillovers being concentrated within a federal lab complex or within states representing agglomerations of labs and companies. Furthermore, qualitative evidence provides some support for the use of patent citations as proxies for both technological impact and knowledge spillovers.

3.3. Technology use indicators

To obtain more detailed measures on a specific industry several researchers have constructed measures of technology use of particular importance to a single industry under study. An influential early paper in this strand of literature was Rose and Joskow (1990) who study the electricity generation industry. They look specifically at the adoption of the 2400 psi technology in steam fired electricity turbines and provide a very detailed characterization of the impact of firm ownership and size in the adoption decision. Comin and Hobijn (2004) take an alternative approach constructing a very wide range of indicators (20 ‘technologies’) and linking these to country-level growth rates over a very long time period (1788-2001). Comin, Hobijn, and Rovito (2006) extend this approach to 115 ‘technologies’, 150 countries, and 200 years.

The approaches that fall under this heading are as varied as the industries or the technologies in the economy. We give a number of illustrative examples that indicate the wide range of indicators that can be constructed. Their unifying feature is that they track a crucial dimension of technological sophistication for the industry under study; often new data is collected.

A very straightforward application is Caselli and Coleman (2001). They simply track the imports of computer equipment for a large number of countries to investigate the determinants of computer technology adoption. They investigate whether adoption, i.e. importing computers, is correlated with other economic variables and find a positive effect of human capital, manufacturing trade openness, high investment rates, good property rights protection, and a small share of agriculture in GDP.

Another example of a more fluid technology usage indicator is Faria, Fenn and Bruce (2003) who investigate the main determinants of the adoption of flexible production technologies (robots, networks, computer automated design, etc.) using a plant-level dataset of Portuguese manufacturing industry. This highlights that a ‘technology’ can mean very different things in different context. Similarly, Van Biesebroeck (2002, 2003a) documents the transition from mass to lean production in the North American automobile industry. Here, technology comprises a whole system, or set of activities.

Swamidass (2003) sent out surveys to all members of the National Association of Manufactures (NAM). The survey contains specific questions about the skill level of employees concerning the use of 21 technologies (categorized into computerized and soft technology). He finds that small plants are slower than larger plants to adopt manufacturing innovations.

Thomas (1999) examines the order in which firms adopt new technologies in the computer disk drive industry. He finds that large firms and incumbents are more likely to adopt earlier than small ones and entrants when innovation does not rapidly make existing technologies and products obsolete.

A number of studies, including Hannan and McDowell (1984, 1987) and Saloner and Shepard (1995) measure and analyze the penetration of Automated Teller Machines (ATMs). These machines introduced a new distribution technology in the banking sector in the 1970s. Far-reaching effects on market concentration, competitive conduct and interaction with clients resulted. Evidently, such a technology usage indicator is industry-specific.

4. Evidence on impediments and facilitators

In the following subsections, we discuss the various impediments and facilitators to technology adoption that have been identified using any of the three sources of information discussed earlier. The unifying theme running through this section mirrors one of the most important messages one can discern from Baldwin and Lin (2002)'s study of Canadian plants: there is no single problem that dominates others. Even more importantly, the frequency with which specific problems are reported varies in nonrandom ways across the actors in the economic system. Cost-related problems (cost of capital, cost of related software development, and increased maintenance expenses) and institutional related problems (taxation related to capital cost allowances, R&D grants, and government regulations) are reported more frequently in younger establishments. Labor-related problems (shortages of skills, problems with training and labor contracts) are reported more frequently among younger establishments with higher growth. Organizational-related problems (poor management attitude and worker resistance) are more likely in larger, older and unionized establishments. Informational problems (lack of scientific and technical information, technological services and technical support from vendors) are particularly prevalent in Canadian-owned establishments.

In Section 4.1, we start by giving an overview of various factors that researchers have discussed in depth in studying (mostly) the manufacturing sector. Throughout, we will qualify the findings in the literature by stressing under which circumstances they have been found to be important; and where possible we discuss how the findings are relevant for policy. Subsequently, in Section 4.2 we focus on two largely exogenous issues – from the point of view of policy makers – that have received particular attention recently, the impact of geographical distance and complementarities between activities or technologies. In the following Section 4.3, we discuss in greater detail two of the most important impediments that can plausibly be viewed as more easily amenable by government policy – financing constraints and difficulties firms face to obtain the right information. Finally we study in detail two technologies, information and communication technologies and computer numerically controlled machinery, and two industries, banking and health care. These technologies and industries have received a lot of attention in the literature and we use them as examples to describe more concretely how previously discussed impediments have effects and what can be done about them.

Two tables in the Appendix summarize the most important studies of impediments and facilitators that are discussed. The first table organizes studies by the impediment they primarily focus on, following the sections of the paper. A summary of the main findings is included. The second table groups together studies by sector, adding additional sectors to the ones discussed in Section 4.5, and indicates the most important technologies studied in each sector.

4.1. General impediments

4.1.1. Competitiveness

A firm's competitiveness has two opposing effects on its likelihood to innovate or adopt advanced technology, first discussed by Schumpeter more than 50 years ago. Competitive leaders have more at stake and innovation might strengthen their position. On the other hand, they might require less innovation because their relative position confers several other benefits, such as visibility in the marketplace and healthy profits.

A recent paper by Aghion, Bloom, Blundell, Griffith, and Howitt (2005) studies the relationship between competitiveness and the tendency to engage in innovative activities theoretically and empirically. In their model, competition discourages laggard firms from innovating, but encourages neck-and-neck firms to innovate. Together with the effect of competition on the equilibrium market structure, these generate an inverted U-shape between the degree of competition in an industry and innovation. They find empirical support for their theory using data of U.K. manufacturing firms. A crucial feature of their model is that laggard and leading firms will behave differently, and moreover that their behavior depends on the market structure in their industry.

For Canada, the empirical evidence indicates that more competitive firms are more likely to adopt new technology than those that are struggling for survival.[13] Baldwin, Sabourin, and Rafiquzzaman (1996) stress that competitiveness relative to foreign (mostly U.S.) firms is most crucial. In particular, they find that plants that label themselves 'competitive with foreign firms' are more likely to use a larger range of advanced technologies, have shorter adoption lags, and are more likely to report an increase in productivity post-adoption. Note that the Canadian technology surveys have spawned a large range of studies investigating the determinants of technology adoption and diffusion. In order to focus on sources that are perhaps less well known to Canadian readers and not as easily accessible we will for the most part discuss foreign evidence and refer to the Canadian studies where a clear comparison can be made.[14]

To explain the tendency for firms to innovate, Aghion *et al.* (2005) argue it is vital to keep track of the competitiveness in the industry, which they proxy by average mark-up, as well as the closeness of firms, proxied by their productivity differences. In several cases, leading firms – which tend to be very 'competitive' or profitable as well – will refrain from innovation because the possibility the laggard will catch up is very small or because the benefits from technological leadership are small. In their model, fostering innovation resembles fostering competitiveness in a sports league. The average quality level of a team (firm) is less important than the dispersion within the league (market). If teams (firms) are more equally matched, we will see better games (more innovation). For government policy this implies that actions that increase the competitiveness of leading firms will have a counteractive effect on innovation if they also increase the distance between the leaders and followers. At the same time, actions that improve the relative position of lagging firms are likely to spur innovation.

[13] Firms self-report themselves as being competitive or not. Presumably, competitiveness is positively related to more frequently used concepts such as profitability, mark-ups, and productivity.

[14] The website of Statistics Canada provides a document "Overview of Statcan program in innovation" which gives an exhaustive overview of the different studies related to innovation that researchers associated with Statistics Canada have carried out over the last decade and a half. A copy can be found here: http://www.statcan.ca/english/freepub/11-623-XIE/2003001/tudescrip.htm The latest update of this document can be found on the following web site: http://www.statcan.ca/english/freepub/11-623-XIE/2003001/indescrip.htm

Technology adoption has another aspect to it that is not modeled in the previous papers. In order to adopt new technologies firms need to possess a minimal level of technical expertise. Baldwin and Rafiquzzaman (1998) show that several measures of overall technological competency reduce the adoption lag in Canadian manufacturing firms. Such an effect has long been known in developing economics. The persistency of the income (and technology) gap between countries is often ascribed to a lack of absorptive capacity in lagging countries. Acemoglu and Zilibotti (2001) argue that many technologies used in developing countries are developed in OECD countries and inappropriate for the local mix of skills. Los and Timmer (2005) provide evidence that such inappropriate technology takes a much longer time to diffuse and is clearly suboptimal for the developing economies.

All of these studies stress that firms are not making their adoption decisions in a vacuum. Hannan and McDowell (1987) present evidence that the adoption of an innovation by rivals increases the conditional probability that a decision to adopt will be made. However, the result can also go the other way. In a study of magnetic resonance Imaging (MRI) adoption in hospitals, Schmidt-Dengler (2004) finds evidence of strategic pre-emption. One firm might adopt earlier than it would have done as a monopolist to gain first-mover advantage and delay adoption by rivals. The presence and adoption decision of rivals will not only influence the potential benefits of adoption, it will also affect the costs. Hannan and McDowell (1987) find important effects of spillovers from technology adoption and the interaction of market concentration and rival precedence, discussed in greater detail below.

Levin, Levin and Meisel (1987) study the effects of market structure variables on the conditional probability of a firm initially adopting the new technology of optical scanners as the innovation spread through the food store industry. In the early stage of diffusion, adoption was most readily by firms with large average store size, which are not members of chains, and operating in less concentrated markets with higher incomes and wage rates. Later on, differences in seller concentration, market share, and size become less important as other firms follow prior adoptions.

The main policy conclusion from this section is that, to the extent that government policies are able to increase the competitiveness (often understood as degree of competition) in an industry or within a country, the effect on technology will be ambiguous. Several of the studies cited here have shown that a more competitive environment can increase as well as reduce the level of innovation or the speed of technology adoption. One has to take into account the relative position of firms that are most affected and the firm's own perception of its competitiveness. The subsequent effect on market structure should not be ignored either. This balanced view is in contrast with the popular assumption that raising the average level of competition is sure to improve technology adoption.

4.1.2. Foreign participation

Given that the pool of knowledge in the world at large exceeds that available domestically, contact with foreigners is likely to facilitate the use of advanced technology. Keller (2004) summarizes the importance of different channels and Section 2 summarized that literature. Here we discuss the way in which foreign ownership, FDI, or licensing facilitates technology transfer.

Pyke, Farley and Robb (2002) find that foreign participation has a powerful impact on new technology implementation in Shanghai manufacturing firms. While state-owned enterprises, privately-owned enterprises, joint ventures, and wholly-owned foreign subsidiaries hardly differ in all other aspects of operation that they study, there are important differences in technology use. Firms with at least some foreign ownership are significantly more likely to use advanced technologies and, even more important, they are significantly more likely to invest in these technologies going forward.

Bellak (2004) surveys several of the difference that have been documented between multinational firms and domestic firms. The differences between foreign-owned and domestic plants have also been noted on several dimensions covered in the Canadian innovation and technology adoption surveys. For example, Baldwin and Diverty (1995) find a positive and significant coefficient on a foreign ownership dummy in a regression explaining the probability of technology adoption. Similarly, Veugelers and Cassiman (2004) present evidence that subsidiaries of foreign multinational enterprises are particularly important to introduce new technologies in Belgian manufacturing.

Importantly, they find that these subsidiaries convey important knowledge spillovers to the local economy, not because they are intrinsically prone to generate spillovers, but rather because they are much more likely to acquire technology internationally.

Griffith, Redding, and Simpson (2002) find that even though foreign multinationals do make up a significant proportion of establishments at the technological frontier, the speed of productivity catch-up between U.K. manufacturing firms does not appear to vary with the extent of foreign presence in the industry. Their maintained hypothesis is that catch-up is spurred by technology spillovers. Bartoloni and Baussola (2001) also do not find much evidence that being part of a corporate group increases the probability of adoption for Italian industrial firms.

Vishwasrao and Bosshardt (2001) postulate that firms in developing countries are even more likely to rely on foreign technology purchases to improve their technology. They use the theoretical framework that includes network effects developed by Katz and Shapiro (1993) to examine the ongoing technology adoption behavior of foreign-owned and domestic firms. Using firm-level data on Indian firms from 1989 to 1993, they find that foreign ownership, firm size and market structure are among the variables that impact a firm's probability of adopting new technology. They also find that the 1991 liberalization of technology transfer policies in India appears to have had a larger impact on foreign-owned firms than domestic firms.

What several of these studies have in common is that foreign ownership or being part of a multinational group might proxy for a variety of differences between plants. Once other differences are controlled for, the differences between domestic and foreign-owned plants become smaller. More research is needed to identify more convincingly which characteristics on which the average domestic and foreign plants differ matter most for technology adoption.

4.1.3. Plant or firm size

One of the most robust empirical regularities in the literature is that large firms and plants are more likely to adopt and use advanced technologies. We do not single out any papers in particular here because there are literally hundreds of studies that find a significant coefficient on a firm size dummy (measured in a variety of ways) using a variety of technology (adoption) dimensions as dependent variable. As with foreign ownership, the interpretation of a significant size dummy should be done with caution.

Rose and Joskow (1990) stress that one should be careful not to jump to the conclusion that large plants or firms are intrinsically more likely to adopt technologies once a firm size dummy is found to be positively correlated with adoption. They find support for a model where opportunities to adopt a new technology are increasing in the size of the firm. In their application of the adoption of 2400 psi steam turbine technology in the U.S., larger firms are also found to adopt the technology sooner. However, larger firms own more generation capacity and will be on the market to replace a turbine more frequently. Since the invention of the new technology, larger firms are disproportionately more likely to have replaced a turbine, and hence been given an adoption opportunity. Keeping opportunities constant, the authors find that the effect of firm size is much reduced.

A simple cross-section is bound to overestimate the effect of firm size. The previous model is just one example why firm size is not exogenous to the occurrence of an adoption opportunity. Similarly, large firms are likely to differ in many, often unobservable, ways from smaller firms – why are they large in the first place? – which makes a *ceteris paribus* comparison difficult. For example, managerial talent or the number of markets a firm operates in are likely to be systematically higher for larger firms, leading them to assign higher benefits to new technologies. Nevertheless, the list of papers that stress the importance of firm size has kept growing over the years. Even studies that are very careful in other dimensions, see for example Swamidass (2003), make strong statements about the importance of firm size without holding adoption opportunities constant. We refrain from discussing several of the recent studies in depth because the Rose and Joskow (1990) paper underscores that one has to be careful drawing conclusions from a significant size dummy.

One notable study, Thomas (1999), stresses further that the difference between large and small firms will not go the same way in each circumstance or in each industry. He examines empirically the order in which firms adopt new technologies in the computer disk drive industry. He finds that large firms and incumbents are more likely to adopt earlier than small firms or entrants when innovation does not rapidly make existing technologies and products obsolete. The author argues that these results are consistent with heterogeneous research capabilities.

Finally, Miravete and Pernias (2006) find evidence that small firms in the ceramic tile industry in Spain tend to be more innovative overall. A crucial innovation in their modeling approach, strengthening their claim, is that they control very generally for unobserved firm differences. Firm size tends to be systematically correlated with other observable and unobservable factors that are shown to relate positively to the likelihood of technology adoption. Controlling for these factors switches the sign on the firm size dummy.

4.1.4. Stock effects

Some theoretical papers assume that adopting a new technology is less costly if current technology use is very advanced. This follows in the tradition of the endogenous growth literature, see Romer (1990), where the ease of inventing new knowledge is independent of the technology level. As a consequence attaining a certain level of technology – adopting a certain technology – would be easier if one starts from a higher level. Empirically, few examples of cumulative effects within a type of technology have been found. Complementarities between different technologies are often reported, and discussed below in Section 4.2.2, but this does not seem to imply that firms that already possess advanced technology in a certain dimension are more likely to deepen it, see for example Gourlay and Pentecost (2002).

One of the first papers to comprehensively test for different effects identified in the theoretical diffusion literature is Karshenas and Stoneman (1993). They present an empirical approach that simultaneously incorporates rank, stock, order, and epidemic effects, which represent the four main theoretical streams in the literature. They find evidence of rank (as proxied by firm size and industry growth rate) and epidemic (endogenous learning) effects, which are discussed in Section 4.1.8. They do not find evidence supporting stock (technology-deepening) and order (pre-emption) effects. The latter two effects are generally derived theoretically by explicitly incorporating strategic considerations. The authors note that their results are likely to be influenced by the type of technology they study – computer numerically controlled (CNC) machine tools – which requires a significant impact on a firm's costs and output for adoption to make sense. No impact of technology on sample attrition is found, which the authors interpret as support for the view that this technology is not sufficiently drastic to illustrate stock and order effects. Furthermore, Karshenas and Stoneman (1993) provide evidence that R&D spending by the firm, its corporate status, or industry concentration have no significant impact on technology adoption – confirming some of the effects discussed earlier.

In a similar study of process technology in the semiconductor industry, Cabral and Leiblein (2001) find no evidence that experience with previous technology vintages or regional technology spillovers influence adoption. These two effects are important dimensions of a potential adopter's ability to access a previous stock of technological knowledge. Hence, they interpret their finding as additional evidence against the 'stock' theories. Only experience with the immediately preceding generation of technology has some effect, but given the fast evolution of technology in this industry one cannot rule out that this is merely the result of persistent unobserved firm quality.

Eeckhout and Jovanovic (2002) develop a dynamic model with knowledge spillovers in production, which can rationalize the persistent inequality in technological intensity between countries or firms, even if the laggards actively engage in R&D or are able to copy best-practice technology. The model contains two opposing forces. Imitation of other firms helps followers catch up with leaders, but the prospect of doing so makes followers want to free ride. The model illustrates that the opposing forces of technological leadership on innovation already discussed earlier can equally come from the cost side as from demand (see before). If the second force dominates, which is the case for their functional form assumptions, it creates permanent inequality. They also find that free-riding is increasing in the size of the spillovers and the ease with which they can be obtained. Using Compustat and patent-citation data they find that copying is highly undirected, which lowers free riding and tends to lower equilibrium inequality. This study highlights that it is extremely difficult to disentangle the effects of market structure and the existing technology level on technology adoption. Focusing on one of these forces in isolation will lead to biased findings.

4.1.5. Internal organization

The literature on the internal organization of the firm, see Aghion and Tirole (1997) and Dessein (2002), stresses that control rights will influence resource decisions downstream in any hierarchical structure. By altering incentives, formal authority will have an impact that communication will never be able to overcome. It is impossible to know in general which organizational structure will lead to the most rapid technology adoption. Delegation of decision power, existence of veto power, and establishing communication structures will not only alter decisions, but also influence agents' incentives to acquire and share information. If the agent's and principal's objective conflict, there is a tension between efficient decision making, which is facilitated by delegation, and furthering the organization's interest.

Several studies have found that the internal organization of the firm has important consequences on the adoption decision. Effects are especially important for ICT or supply chain management technologies that have the potential to influence the entire operation of a firm and not only its production process, see for example Patterson, Grimm and Corsi (2003) or Bird and Lehrman (1993). Much of the economics literature ignores such effects, but the multidisciplinary nature of the technology adoption literature is clearly a plus here.

Factors that these papers stress include organizational structure, integration of supply chain or ICT strategy with overall corporate strategy, past financial performance, external partner pressure, transaction climate and environmental uncertainty. A more elaborate discussion of these effects is deferred to the section on ICT adoption, which is the context where internal organization has come up the most. From a policy perspective, there is little the government can do about these, but it cautions that studies that entirely ignore these aspects risk misattributing effects. This is likely to be a particular concern for studies that include vastly different firms in the sample or studies that lump most differences between firms in a 'foreign ownership' or 'corporate structure dummy'.

4.1.6. Perception of benefits

Obviously, perception of higher benefits will boost adoption, but where do these perceptions come from? The decision to adopt or not to adopt a new technology is inherently forward-looking. Hence, it does not come as a surprise that managers' self-reported perception on benefits have been found to significantly affect adoption rates, see Baldwin and Rafiquzzaman (1998). The same holds for the managers' perception about their own firm's competence. Both are correlated positively with adoption. Interestingly, Baldwin and Lin (2002) find that firms that actually decide to adopt the new technology are more likely to mention impediments than non-adopters. Their explanation for this counter-intuitive finding is that innovation involves a learning process. Innovators and technology users face problems that they have to solve and the more technologically innovative firms have greater problems. They conclude that the information on impediments in technology surveys should not be interpreted as impenetrable barriers that prevent technology adoption. Rather, these surveys delineate challenges inherent to the adoption process that successful firms had to overcome.

It is hard to accurately capture such subjective perceptions. We already mentioned the finding in Karshenas and Stoneman (1993) that industry growth rates are positively related to adoption, which they interpret as support for a 'rank' effect on adoption, but such a measure can proxy for a variety of effects. Weiss (1994) develops a model of the innovation decision process where user firms form expectations over future improvements in current best-practice technology. His empirical study to test the model's predictions is consistent with the central hypothesis that innovations are strongly influenced by expectations.

Sarkar (1998) stresses the success that evolutionary models, as opposed to the neo-classical rational optimization models, have had in explaining certain peculiarities of the diffusion process. In particular, instances of path-dependency have been taken as examples that society can be locked into an inefficient technology. Prime examples are instances of competition between network technologies, e.g. VHS recorders, QWERTY keyboards, or alternating versus direct current. Self-fulfilling prophecies are a feature of many dynamic models and especially in models where state-dependency can be strong, e.g. when technologies exhibit complementarities or where future technological innovations build on existing knowledge, one can expect long-lasting effects of early technology choices.

4.1.7. Uncertainty

More generally, uncertainty about the future state of the world – be it the evolution of technology, the market size, or decisions of competitors – is likely to be important. The real options theory of investment under uncertainty has been masterly summarized in Dixit and Pindyck (1994) and the insights apply equally well to technology adoption. In general, greater uncertainty will lead to delayed adoption, because waiting for uncertainty to be resolved has an option value.

The model in Weiss (1994) incorporates the intuitive fact that under incomplete information firms' expectations on the evolution of the best-practice technology influences their own technology adoption decisions. He provides empirical support for several predictions of the model on a sample of circuit board manufacturers.

Hollenstein and Wörter (2004) investigate the decision to adopt internet-based e-commerce. They conclude that institutional, technological and economic uncertainty, as well as adjustment costs are important explanatory variables. Faria, Fenn, and Bruce (2003) incorporate demand uncertainty and find a strongly negative effect of higher uncertainty on the probability of adoption. Their proxy of demand uncertainty has been used in a number of papers. They postulate that total value added produced in a firm's 3-digit SIC industry constitutes that firm's demand, or is proportional to it. The standard deviation of the growth rate of this series in the years immediately prior to the adoption period studied is used as a proxy for demand uncertainty. It simply captures fluctuations of aggregate value-added around the trend for the preceding period.

While it would generally be impossible for government policy to lower uncertainty about the evolution of technology or demand, other forms of uncertainty can be more readily be addressed. For example, stability in the tax treatment of R&D, capital investments, and corporate profits in general is often quoted as one of the crucial contributors to Ireland's success at attracting foreign direct investment (FDI). The ongoing uncertainty about the proposed revisions to Canada's intellectual property protection laws, in response to widespread dissemination of copyrighted works over the internet, is sometimes mentioned as a drag on Canadian investments in the area.

Hall and Khan (2003) stress that the diffusion process unfolds gradually over time. It inherently involves a trade-off between relatively uncertain benefits and more certain costs. As a result, firms do not decide to adopt or not, but rather whether to adopt now or postpone the decision to a future time period. Viewed this way, it is only natural to use the real options framework to analyze the diffusion process. Slade (2001) provides a nice application to mining investments. Luque (2002) explicitly uses the real options approach to adoption of advanced manufacturing technologies. Consistent with the theory, she finds that plants operating in industries where investment reversibility is relatively easy and with lower degrees of demand and technological uncertainty are more likely to adopt early.

4.1.8. Learning

One of the most intensively researched topics in technology adoption is the extent to which firms learn from other adopters – dubbed the epidemic or learning effect. Given the inherent uncertainty of the costs and benefits of adoption, efficiency for society could be greatly improved if one adopter's experience could be easily shared with others. In this strand of the literature, researchers have struggled to discern between a firm's learning from its own past experience, asymmetric effects of successful and unsuccessful innovations by competitors, and differences between technologies in the extent firms can learn from their own or other firms' experiences. Most data sets covering technology adoption in the manufacturing sector only contain a cross-section of firms and this is obviously an area where panel data will help greatly. The recent availability of a time dimensions in a number of data sets is likely to lead to advances in the years to come.

Bartoloni and Baussola (2001) confirm the importance of the number of other adopters in the industry. The development literature has long documented the effect of "social capital" on many factors, including technology adoption. Simply counting the number of other (potential) adopters is the most straightforward way to measure this input factor, but more sophisticated studies incorporate information on the frequency of interaction between different agents. For a recent example, see Isham (2002), who studies fertilizer adoption in Tanzania.

More generally, Webster (2004) investigates the forces that lead some firms to engage in more innovative activities than others using a survey of 360 large Australian firms. She concludes that the extent of learning, knowledge spillovers, appropriability and managerial approach are more important than industry-specific forces. Fung (2005) evaluates the impact of knowledge spillovers on the convergence of productivity among firms. Using patent citation data, knowledge spillovers are decomposed into intra- and inter-industry spillovers, and internal knowledge flows. Findings suggest that each firm is converging to its own steady-state productivity growth rate, which is conditional on the firm's R&D efforts and the intensity of intra-industry spillovers it receives. Moreover, if technology followers and leaders invest equally in R&D activities, the followers will eventually catch up with the leaders because the former tend to be the ones who receive knowledge spillovers from the latter.

Cameron (1999) is one of the first to use panel data to explore the importance of learning from own experience in a dynamic model of adoption of high-yielding seed varieties. The model is complicated by the existence of unobservable differences between farmers, which hampers the econometrician's ability to tell learning from gradual diffusion in the face of persistent differences between observations. Identifying learning from neighbours' experiences is even more difficult.

Zhang, Fan, Cai (2002) have illustrated this problem very clearly by asking the question which neighbours to learn from. They use geographic information systems (GIS) information to investigate the regional neighbourhood effect on the rate of diffusion of new technologies in rural India. They show that early successful adopters have a larger effect on neighbouring adopters than do the early unsuccessful adopters. Hence, the use of a simple average adoption rate as a proxy for the neighbourhood effect, a common practice in the literature, is likely to be inappropriate.

Information flows are weaker in a heterogeneous population when the performance of a new technology is sensitive to unobserved individual characteristics, preventing individuals from learning from neighbors' experiences. This characterization of social learning is tested in Munchi (2004) using wheat and rice data from the Indian Green Revolution. Differences in the importance of unobservable characteristics for successful cultivation of the two seed varieties are used to draw inferences about social learning on the diffusion process. This study provides a nice illustration that limiting the industry or technology to study can lead to much more informative conclusions. Some evidence is also presented that the lack of social learning for rice, is compensated for by more experimentation by farmers on their individual plots of land.

Recently, the development literature has started to use randomized experiments to control for unobservable differences by randomly assigning households to control and treatment groups. Duflo, Kremer, and Robinson (2005) is an early paper using this approach. In the context of agriculture this has proven to be an excellent way of studying the extent of learning and the impact of other observable differences without having to worry about self-selection effects. Note the discussion in Athey and Stern (2003) on the intricate effects that unobservables can have on a production model with complementarities. Unfortunately, extending the randomized experiment approach to an industrial context is likely to be prohibitively expensive. A number of recent papers (discussed in the next section) use supposedly exogenous changes in patent protection as natural experiments to investigate the extent of innovation before and after the regime change, see Sakakibara and Branstetter (1999), Bessen and Maskin (2000), and Lerner (2004). This is probably as close to randomization as we can hope to get in this context.

4.1.9. Regulation

Technological choice is influenced by regulation and this is most clear in the field of environmental economics. The impact can go either way – helping or hindering adoption. For example, more stringent emissions regulations have spurred electricity generators to invest in scrubber technologies and have lead firms to search for cleaner coal. However, in a study of paper mills and environmental regulations in the U.S., Gray and Shadbegian (1997) find that in states with more stringent regulations total investment is unaffected because plants with high investments in abatement lowered their investments in productive capital. In their study, crowding out between technology investments and direct capital investments is almost complete. Adoption is boosted, leading to cleaner air, but productivity falls.

Kerr and Newell (2003), on the other hand, find that the regulations to phase out lead in gasoline generated more efficient technology adoption decisions in the transition period. Especially the tradable permit system, which allowed firms with high abatement costs to compensate other firms that made pollution reductions in their place, has been found to provide good incentives. The contrast between these two studies indicates, yet again, that one cannot look at the effect of a change – in this case a change in regulation – ignoring the market structure and operation.

Studies that carefully select regulatory changes that can plausibly be considered natural experiments have at least the benefit of being able to ignore anticipatory effects and endogenous changes in regulation. The widespread lobbying by electricity generators and automobile firms makes it unlikely that the previous instances of regulatory change can be viewed as exogenous. Sakakibara and Branstetter (1999) investigate whether strengthening patent laws would induce more innovation. Weak patent protection is often cited as a major cause for the lack of R&D activities in emerging economies. For the 1988 law change in Japan, they only find insignificant increases in patenting or R&D outlays in the data. This lack of response is confirmed through interviews with firm managers.

Lerner (2004) provides contrasting evidence that after the landmark 'State Street decision' opened up the possibility of patenting financial innovations the process of innovation changed greatly. In particular, the ability to file for a patent made size a much more important factor in promoting innovation – industrial patenting has always shown a clear correlation between firm size and propensity to patent. Prior to the regime change, when innovations were not patented, less profitable firms and those with stronger academic ties tended to innovate significantly more. As a methodological aside, this paper is a first to use the number of related Wall Street Journal news stories as its measure of the degree of financial innovation – a new 'technology use indicator' if ever there has been one.

4.1.10. Employee skill level

Not surprisingly, several studies document important interaction effects between the skill level of employees and the propensity for technology adoption by the employer. These effects go both ways. Firms with a highly skilled workforce find adoption costs to be lower and are, ceteris paribus, more likely to adopt. On the other hand, adopters often provide complementary training to their workforce to maximize the benefits they can reap from the new technology. These interaction effects are illustrated for Mexico in López-Acevedo (2002).

In the context of adoption of more advanced agricultural technologies, generally fertilizer or high-yielding seeds, one can more plausibly consider the level of education to be pre-determined. Zhang, Fan, and Cai (2002) document the importance of education as an explanatory variable in the adoption decision in rural India. Foster and Rosenzweig (2004) provide more detailed results that confirm the positive relationship between education and seed adoption for the Green Revolution in India.

It would be interesting to see whether these results could be extended to other sectors of the economy, for example for small or medium sized enterprises where the education level of the owner is likely to be important and pre-determined as well.

4.2. Important exogenous impediments

We now discuss two issues affecting technology adoption that have received particular attention over the last decade. Both the impact of geography and the existence of complementarities between different technologies or different dimensions of a single technology figured prominently in the technology adoption literature in the last decade. To highlight their importance we discuss them in a separate section. Because policy is unlikely to have much influence over these factors, we separate them from two important endogenous factors that will be discussed in the next Section.

4.2.1. Geography

The economic geography literature explicitly incorporates distance in the diffusion process; see for example Autant-Bernard (2001). Simply put, firms are more likely to adopt a new technology from geographically closer neighbors. The actual channels are often left unspecified, but they are often assumed to center around informal meetings by employees of different firms, network opportunities that arise from living in the same areas, more frequent contacts with clients or suppliers that are located close by, etc.

Most studies use regional correlations in productivity levels or growth rates to infer regional spillovers. The maintained hypothesis is then that productivity advances are driven by technological factors. Jaffe, Trajtenberg, and Henderson (1993) show that, perhaps surprisingly, patent citations are also geographically concentrated, even controlling for industry composition. Using direct information on the diffusion of a select list of advanced technologies, geographical nearness of suppliers has been found to decrease the adoption lag, see evidence in Baldwin and Rafiquzzaman (1998). Such geographically concentrated spillovers naturally lead to clusters. Evidence in Rafiquzzaman and Boone (2005) suggests they are exhausted within a distance of 500 km. They also find that the size of the spillovers are extremely large, especially for areas less than 200 km apart.

Keller (2004) provides an excellent overview of international technology diffusion—a particular kind of geography. For most countries, foreign sources of technology account for 90 percent or more of domestic productivity growth.[15] Creation of knowledge is more heavily skewed towards a couple of rich countries, notably the U.S. and Japan, than production or income. At the aggregate level, he finds that importing provides a stronger channel than exporting and FDI is even more important. Similar spillovers have been documented at the firm level, see for example Yasar and Morrison-Paul (2005), and in the literature that studies patent citations as a source of technological diffusion. Hu and Jaffe (2001) document in detail how knowledge flows from the U.S. to Taiwan and Korea can be traced in patent citations.

Bellak (2004) surveys the difference between multinational firms and domestic firms and confirms that multinationals tend to be more technology intensive than firms only selling in their domestic market. This should work to Canada's advantage, as a large fraction of manufacturing firms are foreign-controlled and part of multinational groups. It may however be the case that the most high-tech activities of these firms take place close by their headquarters, which by and large tend to be located outside of Canada. For example, Van Biesebroeck (2006) indicates that in the automobile industry several multinational firms have closed their regional headquarters in Canada. The enormous concentration of automotive R&D in Michigan coincides with the large concentration of automotive headquarters – more than 50% of the largest suppliers to the North American automotive industry are headquartered in Michigan. Dearborn, Auburn Hills, and Troy – the towns

[15] Baldwin and Gu (2003) and Van Biesebroeck (2005a) provide evidence for learning-by-exporting effects in the manufacturing sector of, respectively, Canada and sub-Saharan Africa. Some theoretical models explain the increased productivity level of exporters as the result of learning advanced technologies of international competitors or clients. Van Biesebroeck (2005a) provides additional evidence that exporters produce with a different production technology than domestically oriented firms.

where the Big Three original equipment manufacturers (OEMs) and the two most important suppliers have their headquarters – are particularly popular. To some extent, geographical proximity seems to substitute for the ownership ties between suppliers and client of the old days.

For geographic proximity, as for many phenomena that have only recently gained prominence, data availability severely constrains the applications that are pursued. Lewis (2004) proposes to use the U.S. Surveys of Manufacturing Technology to develop statistics on the technology use of major categories of advanced production technology by state and in large metropolitan areas. If successful, these statistics could be of use in a wide variety of research applications. For example, regionally stratified technology-use data would be useful to researchers interested in the effect that government regulations (minimum wage, environmental regulations, etc.) have on technology use and technical change. These statistics can also be used as an alternative means of asking what effect technical change has on outcomes of interest, such as employment or wages. Lewis' first project is to try to assess how the characteristics of the local work force affect any observed geographic differences in the use and implementation of advanced manufacturing production technologies.

Patent data, which contains geographical information on the inventor and the owner of the new invention, provides an alternative source of information. Almeida and Kogut (1997) examine the innovative ability of small firms in the semiconductor industry regarding their exploration of technological diversity and their integration within local knowledge networks. Through the analysis of patent data, they find that, compared with larger competitors, small firms explore new technological areas by innovating in less 'crowded' areas. They are also to a greater extent tied into regional knowledge networks. These findings point to a unique role of entrepreneurial firms in the exploration of new technological spaces and in the diffusion of their accumulated knowledge through local small firm networks. It indicates that smaller firms exploit knowledge spillovers to a greater extent by looking for geographical proximity of other R&D intensive firms, while at the same time avoiding competition by concentrating their research efforts to more isolated areas of technology space.

Griffith, Harrison, and Van Reenen (2003) examine whether U.K. firms that locate their R&D activity in the U.S. benefit more than other U.K. firms from knowledge spillovers originating from U.S. R&D. Patent data provides a firm level measure of the location of innovative activity, which enables the identification of knowledge spillovers associated with 'technology sourcing'. While they do find evidence for such increased spillovers, the data does not allow a clear differentiation between technology sourcing and an absorptive capacity effect.

Several case studies have explored the impact of geographical proximity on technology adoption in greater detail. Ivarsson and Alvstam (2005) use firm-level data, collected at the bus and truck plants of AB Volvo in Brazil, China, India, and Mexico, to analyze the extent to which "local" suppliers, located near the assembly plants, are in a better position than other suppliers in the host country to take advantage of the technological assistance that Volvo provides as part of its ongoing business relations. The paper finds important effects of agglomeration and spatial proximity on the establishment of technology linkages between foreign transnational corporations and suppliers in developing countries. Geographic proximity is found to increase opportunities for the suppliers to absorb external technology. For many of the smaller domestic companies that make up the dominant share of Volvo's local suppliers, low transaction and communication costs and the opportunity to interact regularly with Volvo are an important determinant of the successful absorption of external technology.

Finally, Bergman, Feser, and Kaufmann (1999) survey studies that examine regional influences on enterprise-level technology adoption behavior. They criticize most of these studies for selecting either single indicator technologies (e. g., computer numerically controlled machines) or relatively crude summary measures of multiple technologies for use in diffusion models. They argue that firms typically utilize production technologies in complicated bundles and derive measures of process technology sophistication that take better account of the complexity of what may be described as the 'technology portfolios'. In the economics literature, such cross-technology spillovers are generally called complementarities and are analyzed in more detail in the next Section. One of their innovations is to exploit information on multiple technology use by examining rates of joint technology adoption and utilization among enterprises. They propose to use these joint-adoption decisions of firms as an index of technology use that might be used as dependent variables in micro-level studies of regional determinants of technology adoption.

4.2.2. Complementarities

Complementarities are an important aspect of many new technologies. The return to the adoption of one new technology is often increasing in the adoption of other technologies. As a result, firms can be stuck with low use of advanced technologies, because adoption would only be profitable if a range of technologies would be adopted jointly. Milgrom and Roberts (1990) provide an important early characterization of the concept with as example the adoption of the 'modern manufacturing system'. Flexible machine tools and programmable, multitask production equipment is complementary to production of smaller batch sizes. A just-in-time inventory management system is obviously complementary to an electronic communication system to interact smoothly with one's suppliers. They prove that if different aspects of a technology system interact to increase the benefits associated with each part, firms will not adopt the different activities that make up a system separately, but make an all-or-nothing choice. Intermediate systems that combine activities from different systems will be unstable.

Empirically, one can analyze complementarities by looking for instances of joint adoption of several new technologies. An alternative is to look for positive interaction effects of two activities in a firm's profit or production function. Athey and Stern (2003) provide a general empirical (measurement) framework to distinguish the existence of complementarities from the simultaneous effects of an omitted variable on two otherwise independent technologies. A crucial insight they provide is that one can control for such an omitted variable, or any other correlation between technology-specific errors, if one has access to technology-specific instruments. However, if there are system-specific error terms which are correlated with any other variable in the model, be they observable or unobservable, identification of complementarities becomes near-impossible.

Ichniowski, Shaw, and Prennushi (1997) provide one of the best examples of studies that investigate the existence of complementarities between different human resource practices. They find, for example, that the productivity effect of incentive pay is enhanced if the workplace also allows more flexible job assignments and stresses teamwork. Arora and Gambardella (1990) investigate whether strategies of external linkage of large firms using biotechnology are complementary to one another. For a sample of large U.S., European and Japanese chemical and pharmaceutical producers they find such evidence, even after controlling for a rich set of firm characteristics. In particular, they find that the probability of establishing agreements with other firms, research agreements with universities, minority partnerships with new biotechnology firms are positively correlated.

The literature is still in full development as the wide range of research methodologies highlights. Fleming and Sorenson (2001) find support for complementarities using patent citation data. They view technological innovation as a complex adaptive system where actors search over 'technology landscapes'. Hollenstein (2002) relies on cluster analysis to investigate complementarities in the Swiss service sector. Using information on a large number of technology indicators he investigates which indicators are frequently found to occur together and identifies five "modes" of innovation. Wozniak (1993) investigates a similar complementarity between information acquisition and new technology adoption. Firms face the joint decision whether or not to adopt a new input and to invest in technical knowledge. The previously discussed survey of R&D spillovers, Wieser (2005), puts complementarities in a different light. Rather than looking at the interaction between technologies, one can also look at the impact of R&D spending at one firm on the productivity in nearby firms. Several studies attempt to estimate statistically the part of productivity growth that can be attributed to such arms-length R&D activities.[16]

Focusing on technology adoption in particular, we mention three studies that control explicitly for the endogeneity problems in Athey and Stern (2003). Miravete and Pernias (2006) provide evidence for the existence of complementarities between production and innovation strategies. Their approach is able to distinguish between complementarities and correlation induced by unobserved heterogeneity. The model is applied to the Spanish ceramic tiles industry where the adoption of the single firing furnace in the 1980s facilitated the introduction of new product designs as well as to opening new ways of organizing production.

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[16] A related literature has also looked for, and has frequently found, similar spillover effects of FDI on the productivity of domestic firms in related industries.

Åstebro, Colombo, and Seri (2005) analyze the simultaneous diffusion of multiple process technologies that are related. Their econometric model allows them to distinguish between complementarities, one-step-ahead non-causality and simultaneous independence. Results indicate significant complementarities between computer automated design (CAD) and CNC technologies. Prior adoption of either of the two technologies has a large effect on the posterior adoption of the other one (a stock effect). In addition, simultaneous adoption is found to be more likely than adoption of the two technologies in isolation. Consistent with the presence of complementarities they also find evidence of substantial price cross-effects: a decrease in the price of CAD (CNC) increases the adoption probability of CNC (CAD).

Van Biesebroeck (2005b) investigates activities that automobile manufacturers can engage in to lower the productivity penalty associated with the production of a greater variety of car models within a single assembly plant. Traditionally, plants were dedicated to produce only a single or a few related models, but the proliferation of models in the market place has forced firms to produce as many as eight models within a single plant. Using activity-specific instruments as advocated by Athey and Stern (2003), he finds that the adoption of flexible production technology and reduced outsourcing of assembly steps are complementary to the production of increased variety.

4.3. Important endogenous impediments

We separate the discussion of two more important impediments that have received a fair bit of attention in the literature – the difficulty of obtaining financing and accurate information – from the previous two impediments because these can be more plausibly be influenced directly by government policy.

4.3.1. Financing

Financial constraints seem like an obvious impediment to technology adoption. These have been shown to restrict firm investment in capital equipment and inventory (see Hubbard (1998) for a survey). Regarding technology adoption, the importance is not as clear-cut as even unconstrained firms are often financing new technologies out of retained earnings. The large upfront fixed costs that technology adoption often entails does suggest that credit could play a role as firms might reallocate their financial resources and finance ongoing operations with loans and use retained earnings for new technology adoption. For governments to alleviate credit constraints, they first have to identify them. We will also discuss some studies that highlight the difficulty in identifying constrained firms.

A number of studies have focused on agriculture, because credit constraints are much easier to identify in this context, given the small scale of most firms. Dong and Saha (1998) identify credit constraints as one of the prime explanations for adoption inertia. Rather than focus on the decision to adopt or not, they study the timing of adoption. A key result of theirs is that constrained firms are even more likely to await the resolution of uncertainty. Given that adoption of a new technology often entails relatively large fixed costs, the decision incorporates an inherent non-diversifiable risk and risk-averse small firms face a very high hurdle. They develop a double-limit hurdle model to analyze adoption inertia and intensity of use of a divisible technology. The widely used Probit and Tobit models are shown to be special cases of the general framework, but these are both dominated by the double-limit hurdle model.

The paper also contains a number of important empirical findings on related issues. The results suggest that the impact of other factors such as innovation-related information, firm size, education, and income undergo marked changes during the diffusion process. These factors are likely to have significant and positive effects on the adoption intensity in the early years of innovation diffusion. In subsequent years their impact weakens considerably. Thus, the effectiveness of policy initiatives designed to encourage adoption – dissemination of information about the new technology, education programs, income incentives, and complementary input subsidies – may be significantly higher in the early years of innovation diffusion. The results also show that a scale bias is likely to exist only in the early stages of innovation diffusion. In this study, the relation between adoption intensity and firm size switched from being positive to negative in less than a decade. Therefore, in the long run, policy initiatives aimed at a more equitable resource distribution are unlikely to hinder technological change.

Another study of the agricultural sector, Zeller, Diagnea, and Mataya (1998), finds that credit constraints which are tied to limited market access make adoption less likely. Most cash crops require substantial capital investments and farmers that could benefit most from income diversification are least able to adopt the new crops because of credit constraints. At the same time, while the agricultural credit program they study had a large impact, they also show that access to complementary inputs cannot be overlooked and that wrong price signals from the output market can easily misdirect production decision. They also show that the rapid adoption of tobacco as a cash crop was stimulated enormously by a policy reform and related institutional changes in the tobacco sub-sector that granted quotas to farmers. Overall, they paint a relatively optimistic picture of the potential for policy interventions.

In contrast with the previous two studies, Wozniak (1993) finds reverse effects. A farmer that has a reliable source of non-farm income is less dependent of farm output and is more financially diversified – as was argued before. However, Wozniak (1993) finds that even though they are more *able* to finance the adoption investments, they have *less incentive* to do so. The empirical results show diffusion to be an increasing function of financial stress, which is negatively correlated with the availability of non-farm wage income. In this context, financial support by the government could lower technology adoption.

As was the case for several of the earlier impediments analyzed, the wider context cannot be overlooked here either. Klonner and Gine (2005) study the diffusion of plastic reinforced fiber boats in a fishing village in Tamil Nadu. They specifically analyze the dynamics of income inequality during this process to verify how uneven adoption is distributed among the population, especially if markets do not function properly. While the microeconomic literature on technology adoption and diffusion focuses on “who” and “when,” the macroeconomic literature has focused on the overall impact of globalization on inequality. In this paper the authors bring these two strands of the literature together and they document the importance of credit constraints in the adoption process.

Going beyond the agricultural sector, it becomes much harder even to identify the existence of credit constraints. Bigsten *et al.* (2003) investigate whether firms in sub-Saharan Africa's manufacturing sector are credit constrained. The fact that few firms obtain formal credit is not sufficient to prove constraints, since certain firms may not have a demand for credit while others may be refused credit as part of profit maximizing behavior by banks. To investigate the question, they use direct evidence on whether firms had a demand of credit and whether their demand was satisfied in the formal credit market, based on panel data on firms in the manufacturing sector from six African countries. Of those firms with a demand for credit, only a quarter obtained a formal sector loan. The analysis suggests that while banks allocate credit on the basis of expected profits, micro or small firms are much less likely to get a loan than large firms. The authors also find that outstanding debt is positively related with obtaining further lending. It suggests that a principal constrain to accessing the credit market, especially for smaller firms, takes the form of an entry barrier.

Still on the manufacturing sector in less developed countries, Brandt and Zhu (2005) study firms in Shanghai, China where access to finance differs considerably by ownership. They find that given the same technical capacity, firms with better access to cheap bank credit are more likely to adopt larger technology projects and invest more in imported equipment from technologically-advanced countries. On the other hand, the return to technology investment differs significantly across firms. In particular, firms with better access to cheap credit have significantly lower project profitability and capacity utilization. These results have important implications for the role of financial development in technology diffusion. They suggest that relaxing credit constraints will not automatically improve outcomes.

Hubbard (1998) presents an extensive overview, with a complete literature survey, on the impact of capital market imperfections, focusing mostly on the manufacturing and service sector in developed countries, especially the U.S. A major topic of the survey is the impact of finance constraints on investments in general. He cites several studies that have found particularly important effects on small firms. Giudici and Paleari (2000) provide further evidence about the potential effects on innovation of providing finance to small firms, using a survey of Italian technology based firms.

Cunningham (2004) uses a sample of publicly traded Canadian firms to distinguish between the impact of finance or credit constraints and social learning on inventory investment and capital investment decisions. Using substitution between trade and bank credit, she finds clear evidence of credit constraints. The wealthy firms’ trade credit usage is independent of bank credit, which implies that they are not finance-constrained. The poorest firms are constrained in both trade credit and bank credit. This research suggests that from 1988 to 1998, most Canadian firms faced some degree of credit rationing, producing a pro-cyclical pattern in aggregate trade credit use. At the same time, in a case study limited to semiconductor plants, she finds that social learning appears to influence the decision to adopt new technology. According to the estimates in Cunningham (2004), a 1% increase in the number of other plants that have suspended their investment project generates a 3% increase in the probability of suspension by a plant adopting new technology. Firms investing in conventional technology seem to engage in a 'war of attrition' since they are less likely to suspend their project if other suspensions occur.

The inter-firm diffusion of new technology is also affected by finance constraints. Canepa and Stoneman (2004) document such evidence using data relating to the adoption of CNC machine tools in the U.K. They find that financial constraints significantly delay or even obstruct the diffusion process. In a previous paper, Canepa and Stoneman (2003), use information from two waves of the (European) Community Innovation Surveys CIS2 and CIS3 to document finance constraints in the U.K. and other European countries more generally.

Bond, Elston, Mairesse, and Mulkay (2003) construct company panel data sets for manufacturing firms in Belgium, France, Germany, and the U.K., covering the 1978-1989 period. They estimate empirical investment equations to investigate the role played by financial factors in each country. A robust finding is that cash flow and profits terms appear to be both statistically and quantitatively more significant in the U.K. than in the three continental European countries. This is consistent with the suggestion that financial constraints on investment may be relatively severe in the more market-oriented U.K. financial system.

4.3.2. Lack of information

In Section 4.1, we discussed a number of important impediments that are all related to the lack of information that potential adopters face: perception of benefits (4.1.6), uncertainty (4.1.7), learning (4.1.8), and regulation (4.1.9). In addition, the internal organization of the firm (4.1.5) has also proven to be an important influence on the adoption decision and the speed of diffusion. In this Section, we survey a number of papers that analyze the way in which firms manage their information and how outside institutions can help disseminate useful information. For government intervention to be successful, it is instructive to learn from these examples where firms have reorganized their information processing themselves or where outside institutions have been set up to facilitate information sharing.

Using information from the French 1998-2000 Community Innovation Survey (CIS3), Kremp and Mairesse (2004) find strong effects for the use of four knowledge management policies. Those include (i) promoting a culture of information and knowledge sharing, (ii) motivating employees and executives to remain with the firm, (iii) forging alliances and partnerships for knowledge acquisition, and (iv) implementing written knowledge management rules. The micro-econometric analysis for a representative sample of manufacturing firms indicates that these policies contribute significantly to a firm's innovative performance and to its productivity. The larger the firms and the stronger their connection with technology-intensive industries, the more likely they are to set up knowledge-management policies. The impacts of adoption of the four surveyed practices on performance are not completely accounted for by firm size, industry, research & development (R&D) efforts or other factors, but persist to a sizeable extent after controlling for all these factors. This indicates that firms have considerable scope to obtain a comparative advantage over rivals by actively managing their knowledge creation and maintenance.

Evidence on learning-by-doing and organizational forgetting from the aircraft industry, see Benkard (2000), is consistent with such effect. Learning-by-doing has traditionally been very important in driving the cost down over the life of an aircraft's production cycle. Benkard (2000) provides evidence that after a period of low output, productivity is reduced from its trend growth, controlling for cumulative production. When demand picks up the average production costs exceed what one would have predicted based on a learning-by-doing model. He interprets this as the impact of organizational forgetting, which he conjectures is related to staff attrition in the low-output periods (the second knowledge-management policy in the previous study).

Even though knowledge is clearly important, it is not obvious that outsiders can easily provide it or affect its usage. Anderson and Newell (2004) analyze technology adoption decisions of manufacturing plants in response to government-sponsored energy audits. Overall, plants adopt about half of the recommended energy-efficiency projects. Using fixed-effects logit estimation, the authors find that adoption rates are higher for projects with shorter paybacks, lower costs, greater annual savings, higher energy prices, and greater energy conservation. Plants are 40% more responsive to initial costs than annual savings, suggesting that subsidies may be more effective at promoting energy-efficient technologies than energy price increases. Adoption decisions imply firms expect a return of 50–100% before going ahead, which is consistent with the investment criteria small and medium-size firms state they use.

A policy implication of the study of the agricultural sector by Wozniak (1993) is that public and private information sources have different audiences. To enhance the return on information dissemination activities, and better serve their clientele, policies and practices of information providers should reflect the attributes of potential adopters. For private supply firms, providing partially processed technical information might best accommodate their customers. For example, private supply firm demonstrations (like those at trade shows) might best serve as a means to promote or introduce new technologies. Detailed information, however, about the profitability of adoption might be difficult to communicate in this medium. On the other hand, extension services can target higher educated and larger scale operators, who have a greater capacity for processing information on their own.

A business association is one institution that is often created specifically to facilitate the dissemination of information. They provide a venue for firms in the same industry to network and exchange experiences, but often also aggregate and publish detailed information on the industry – both historical and forward-looking. The problems of rent seeking and of state regulators being captured by business associations have been prominent among the concerns of economic development theory. However, business associations can serve other roles as well. For example, Perez-Aleman (2003) illustrate that they can lead to "the building of new institutions that foster improvements in economic performance through arrangements that emphasize goal setting, problem solving, and continual evaluation of progress toward defined goals." Using a learning-centered approach he analyzes how government-business relations can contribute to economic development. He uses case study material based on Chile's agro-industry business association FEPACH to illustrate how innovative state policy coupled with private firms' efforts led to the group-based coordination that fostered rapid diffusion of new technology and production organization among Chilean enterprises. In particular, he discusses the institutional reshaping of the business association and business-state relations to encourage learning and advance a process of development.

Similarly, Heidenreich (2005) illustrates the importance of cooperation between political actors and business associations, but also enterprises and trade unions, in achieving the transformation of a traditional industrial region (Nuremberg) into a technology and service-based one. The cooperation took the form of the provision of 'local collective competition goods', which combine technological, organizational and scientific capabilities of all parties. In the Nuremberg case, a new regional steering committee facilitated the integration and renewal of formerly isolated regional capabilities into a coherent regional innovation systems. In particular, inter-organizational patterns of cooperation, communication and competition were supported. In the paper are more examples, contrasting East and West Germany, of how the increasing uncertainties of an internationalized knowledge society requires more open-ended and experimental patterns of regional policies.[17]

Especially for small and medium-sized enterprises, business associations can provide a useful function disseminating information. Vanhaverbeke (2001) indicates that the location of firms in business districts is not very effective in cases where innovation is specific to the 'value constellation' firms operate in. He argues that networks are often customer-oriented rather than industry or technology based. Studying the construction and home furnishings business cluster in Belgium, he finds that business associations have been crucial in establishing new networks between firms that fit their current needs better than traditional patterns of interaction. By providing a wider information base, business associations can help firms avoid being locked in by traditional ways of operating.

[17] For example, in Leipzig, the main challenge was to integrate the existing firms into regional networks in order to enhance their innovative capabilities.

In spite of the many success stories, not all interventions work. Schmitz (1999) discusses leather footwear firms in the Sinos Valley in Brazil where firms had stepped up cooperation in response to intensified global competition. In spite of close cooperation and forming a tight network, the participating firms have not been able to generate export success. Bilateral vertical cooperation, contributing to a major advance in raising product quality, speed of response and flexibility all rose. Upgrading in other areas such as marketing, design and image was attempted in an ambitious program of multilateral cooperation. If complementarities between different strategies are important and if there are local spillovers of innovations, one should expect large payoffs from such cooperation, but these did not materialize. Three problems are identified: (i) upgrading was largely limited to the sphere of production, (ii) some leading enterprises put their alliance with a major global buyer above cooperation with local manufacturers; and crucially (iii) the state failed to mediate at critical moments between conflicting business associations and entrepreneurial alliances.

4.4. Evidence from specific technologies

It would be difficult to complete a literature survey on technology adoption without extensively discussing computer numerical control tools and information and communication technologies. These two technologies have been studied most extensively in the literature and several innovative models are first estimated for either of these two technologies. Given that CNC tools are particularly important in advanced manufacturing sectors and ICT can convey important strategic advantage, especially to service sector firms, these two technologies provide a useful contrast in the sectoral dimension as well. Finally, CNC is inherently a technology that affects production, although an effect on the internal organization of teams is also discussed. ICT, on the other hand, has the potential to bring a firm closer to its clients and it has the potential to radically affect the internal organization of the firm.

4.4.1. Computer numerical control tools (CNC)

Several of the papers discussed earlier draw on the experience of firms adopting (or not adopting) CNC tools. In this section we bring together a number of impediments that have been particularly important for this technology. Helper (1995) and Karshenas and Stoneman (1993) both investigate the circumstances under which firms adopt CNC machine tools. One finding is that short contract duration between suppliers and clients significantly hampers adoption. For firms where adoption would be efficiency improving, raising the commitment of customers, in the form of lengthening contracts by one year, would raise the adoption rate by 30%. Other circumstances that are shown to be important in raising adoption rates are output growth in the user industry and firm size. Perhaps surprisingly, industry concentration, R&D spending, firm age and corporate status did not have a significant effect on adoption.

Cabral and Leiblein (2001) analyze the adoption of process innovations using evidence from the semiconductor industry and find important learning-by-doing effects. In addition to analyzing CNCs in Mexico, Lopez-Acevedo (2002) also look into the determinants of the adoption of automatic equipment, machinery tools and robots.

Arvanitis & Hollenstein (2001) study the adoption of what they call Advanced Manufacturing Technology (AMT) using Swiss micro data. They investigate the same set of explanations studied in Karshenas and Stoneman (1993) and much of the preceding literature in a consistent framework. Their findings provide a good overview of the consensus estimates in much of the literature. Rank effects and learning from the use of previous technology vintages tend to be minor. In contrast, effects for complementarities between various functional groups of the technology and firm or plant size tend to be large.

Using the same data set, Arvanitis, Hollenstein, and Lenz (2002) find significantly positive effects of the Swiss government programme to promote the diffusion of AMT. The main feature of Swiss technology policy is the low weight it places on direct measures for fostering innovation in the economy. It is primarily oriented towards creating a favorable environment for the introduction of new products and production techniques, whether such innovations rely on firm-internal research and development or on the adoption of novelties generated by other firms or institutions. This framework-oriented policy is supplemented by a number of specific measures to stimulate rapid diffusion of selected basic technologies which are considered to be relevant for a broad spectrum of industrial activities.[18]

Canepa and Stoneman (2004) study financing constraints, again using data on CNC tools. They find important nonlinearities in the effects. In particular, firms near the break-even point are disproportionately affected by financing considerations, while the most profitable potential adopters are not affected at all. For a technology with high fixed costs such as CNCs this finding is intuitive. However, the non-linearity with respect to profitability makes policy prescriptions difficult. If there are financial constraints, then government assistance to overcome such constraints appears appropriate. However, if the constraints mainly bind upon firms that are only marginally profitable, there would be considerable problems in separating out those firms that are temporarily suffering ill fortune but merit support in the adoption of new technology from those that are inefficient and for whom support is likely to be wasted.

In a series of related papers, Åstebro (2002, 2004) and Åstebro, Colombo, and Seri (2005) investigate the importance of learning, complementary inputs, and technological complementarities. Many costs associated with learning are found to be lumpy and sunk, which leads to a higher probability of adoption if they can be shared over more output or with complementary inputs, such as computer aided design (CAD) tools. As a result, larger plants and those that also use CAD technology will adopt CNC tools more quickly. They

[18] The main issues that the government program wanted to address were a knowledge deficit in the use of AMT (qualified manpower), its interaction with the organization of production, and interaction between polytechnics (technical education) and firms. The driving guidelines were threefold: first, the program had to take into account the interrelatedness of technical, organizational and human (knowledge) aspects of the adoption of AMT; second, promotion should take place at the regional level to make use of local spillover potentials and lead in the long run to an increase of networking among firms and among firms and research/education institutions; thirdly, the program should only help to overcome bottlenecks in the early phase of adoption, therefore it was to avoid that expectations of permanent subsidizing would arise. The practical organization was organized through seven regional ATM centers, which operated between 1990 and 1996. Three types of measures were either directly delivered or arranged by the AMT centers. First, they provided information and training ranging from “one day information” up to “two years full-time training courses”. A second service was consulting aiming either at supporting the realization of a specific AMT project or at preparing the introduction of AMT in a firm by means of an analysis of its specific needs and potentials for this technology which led to the formulation of an “adoption plan” integrating technical, organizational and training aspects. Third, the program subsidized also development projects in the field of AMT typically based on joint-ventures of firms with polytechnical institutes (where the firms had to bear at least 50% of the project costs).

also find important complementarities in different advanced manufacturing technologies that could result from the fact that they all require complementary investments in non-capital inputs, such as employee skill. If this finding is confirmed, policy interventions could easily target education or more focused training programs, and have effects on a range of technology adoption decisions.

O'Farrell and Oakey (1993) indicate that the frequently observed correlation between employee skill level or plant size and the probability of adoption could also be the result of reverse feedback. They find important post-adoption effects on employment level, skill upgrading, and pay scales after the introduction of CNC machine tools in U.K. manufacturing firms. In addition, they find few differences between the effects in core and peripheral regions, i.e. South East England versus Scotland or Wales. They do find, however, that CNC adoption has led to an increasingly polarized workforce, with highly skilled employees becoming more concentrated in fewer large firms.

Battisti and Stoneman (2005) examine the intra-firm diffusion of new process technology, in particular the diffusion of CNC machine tools within firms in the U.K. engineering and metalworking sectors, and confirm the importance of firm organization. They present evidence that even intra-firm diffusion of new technologies can be a lengthy and slow process. The empirical analysis does not reject the hypothesis that profitability considerations are important and it isolates a number of firm characteristics as of special relevance, including firm size and the use of complementary technologies and managerial techniques.

4.4.2. Information and Communication Technologies (ICT)

The recent literature on the adoption of ICT is vast and we cannot do it justice here. A vast range of issues related to businesses' (as opposed to consumers') adoption and diffusion decisions of ICT are discussed in the forthcoming chapter in the new *Handbook of Economics and Information Systems*, by Forman and Goldfarb (2006). The article contains a 15 page bibliography focussing exclusively on the adoption of ICT by businesses.

As an example, we mention the recent study by Fabiani, Fabiano, and Trento (2005). They investigate the information and communication technology adoption choices of a sample of

1500 Italian manufacturing firms. Given that most technologies eventually diffuse to the entire industry, all adoption effects can be interpreted as timing of diffusion effects. Most of their results are illustrative of many studies that look at ICT adoption.[19] The most important firm-specific determinants they identify are firm size, human capital, composition of the workforce, and indicators that capture the internal organization of the firm. In particular, *changes* in a firm's organizational structure lead to subsequent adoption. Given the network aspect of many ICTs, particularly internet-based applications, they also investigate whether the local industry affects adoption patterns even after controlling for individual characteristics. The size, human capital, and workforce composition of the industry in a firm's local environment turns out to have a significant impact, as well as the presence of large firms.

In some firms, ICT technologies can have an important effect on production efficiency, much like the CNC tools discussed earlier. Patterson, Grimm and Corsi (2003) cite a manager who noted: "With almost daily technology advancement globally in every facet of the business, organizations need to synchronize by adopting and implementing new electronic commerce and supply chain technology in order to protect market share, not to mention improve market penetration." They develop a model of key factors influencing the adoption of supply chain technology. They hypothesize that – amongst others – firm size, organizational structure, past organizational structure and environmental uncertainty affect the pace of technology adoption and generate a survey to test the model.

While there is a lot of evidence that ICT has contributed significantly to the surge in labor productivity growth in the U.S. in the late 1990s, no such evidence exists for Canada. Moreover, Khan and Santos (2002) find that there was no acceleration in the contribution of ICT use to output growth in Canada, nor was there an acceleration in the effect of capital deepening in ICT. Disaggregating the effects further, the authors find a slight compositional change towards computer hardware, but not for software or telecommunications. It is sometimes suggested that the weak Canadian dollar has delayed investments by Canadian firms as most ICT equipment is purchased from the U.S. In

[19] Especially in this Section, we cannot hope to be exhaustive. A simple search on "impediments" and "ICT adoption" in the Econlit search engine returns 32 papers exploring topics that are extremely similar to the ones discussed in the Fabiani, Fabiano, and Trento (2005) study. Especially the impact on small and medium-sized firms and local spillovers have received a lot of attention.

recent years, when the dollar strengthened, Canadian business investment has grown more quickly than in the U.S., but it will take time before we will be able to evaluate the effects.

A report on the impact of survey methodology for the Canadian Federation of Independent Business, Mallett (2001), indicates that answers to a variety of questions for web-based respondents differ significantly from answers obtained using traditional survey techniques, such as mail or telephone surveys. The report provides evidence on the much larger uptake of ICT by large firms compared to small and medium-sized enterprises. Similar differences between web-enabled and other consumers exist and adopting e-commerce by Canadian firms becomes indispensable to reach their full market potential. The report also argues that to avoid drawing biased or incomplete conclusions from marketing research, firms should not ignore the online market.

A later study still for Canada, Charles, *et al.* (2002), draws from the first Statistics Canada survey on the uptake of e-business by Canadian firms. Small and medium-sized enterprises are still found to lag behind larger firms. In 2001, 68% of small firms accessed the internet compared to 94% of large firms. The number of small firms with a web site, at 24%, lags even further behind larger firms, 74% of which have an online presence. The respondents' perceptions of barriers to e-business are particularly instructive. The most common cited reason is that a firm's goods or services simply do not lend themselves to the internet, a percentage that is likely to fall over time as the functionality of the internet increases. The next most important reasons are a desire not to disrupt the current structure of the firm and existing business models. Only further down the line are technological barriers such as security concerns, cost of development and maintenance, and lack of skilled personnel.

In spite of the barriers to adoption, electronic commerce in Canada has grown from $5.7 billion in 2000 to over $28 billion in 2004; see Noce and Peters (2005). The perceived barriers have also changed over time, which can be tracked using the subsequent years of Statistics Canada's Surveys of Electronic Commerce and Technology. Not surprisingly, almost a quarter fewer firms respond that their goods and services do not lend themselves to internet transactions by 2003. Uncertainty about the benefits of e-commerce has also declined considerably. In contrast, security concerns have increased and so have expectations of costs. Particularly important is that changes vary by firm size and sector, suggesting that policies aimed at encouraging e-commerce adoption must be specific to both firm size and industry sector.

The paper by Baldwin and Sabourin (2001) studies the impact of ICT adoption on the industrial structure in the Canadian manufacturing sector. The study finds that a considerable amount of market share is transferred from declining firms to growing firms over a decade. At the same time, the growers increase their productivity relative to the decliners. Those technology users that were using communications technologies or that combined technologies from several different technology classes increased their relative productivity the most. In turn, gains in relative productivity were accompanied by gains in market share. Other factors that were associated with gains in market share were the presence of R&D facilities and other innovative activities. Dufour and Tang (2005) provide more recent evidence that confirms the importance of ICT adoption in improving the competitiveness and efficiency of firms. They find in particular that the most successful firms seem to be those that can integrate ICTs with business practices, such as cross-functional working teams, benchmarking, and just-in-time inventory control.

A crucial difference between ICT and more production-oriented technologies is its potential to affect the internal organization of the firm. It is no surprise then that the internal workings of an organization have frequently been found to have important implications for the adoption process. Bird and Lehrman (1993) stress the often overlooked impact of the context in which technology adoption takes place. Studying adoption of IT they find important interactions with the organization and the dynamics of change. In particular, issues of control, who is in charge of the decision making, organizational learning, and inter-organizational interaction proved vital in steering the adoption process. Similarly, Hollenstein (2004) identifies the importance of New Workplace Organization (NWO) as a determinant of the adoption of ICT, as well as the reverse relationship, i.e. the impact of ICT on the adoption of NWO.

The expected use of the technology post-adoption also has important effects on the preceding adoption decision. Evidently, the internal workings of the firm, or at least the perception of the internal workings by the agents in charge of the adoption decision will have such indirect effects. Hart (1996) identifies the following four factors as the greatest barriers that constrain or preclude the use or implementation of inter-organizational computer networks: proprietary technology, contract specifications, phase of design development, and organizational culture. Factors that are found to enhance efficient use of the network include compatible CAD tools, electronically-oriented design support tools, and most interestingly, trust between the design teams.

4.5. Evidence from specific sectors

Finally, we mention a number of papers that study the banking and health care sectors. While we did not focused on nor excluded any sectors or technologies in the previous sections, inevitably many more studies looked at manufacturing (or agricultural) firms. This focus did not necessarily stem from a greater use of technology in manufacturing relative to services, but data availability tends to be much greater in manufacturing or agriculture. In addition, it is often easier to define a new technology if it is used to make a tangible object. Measuring output in the service sector has been a persistent challenge for economists. Hence, a technology that improves service production is equally hard to identify.

4.5.1. Banking

Some of the earliest rigorous papers on technology adoption, Hannan and McDowell (1984, 1987, 1990), study the adoption of automatic teller machines (ATMs) by banking firms in the U.S. The first paper studies the impact of market structure in particular and finds that banks operating in more concentrated local banking markets register a higher conditional probability of adopting the new technology. An advantage of looking at one particular technology in a single industry is that because of regulatory restrictions – banks are only to operate in a single state – the degree of competition in a local market can plausibly be viewed as pre-determined, especially in the earlier period.

Hannan and McDowell (1987) investigate firm reactions to rival precedence in the same ATM adoption process. It is found that the adoption of this innovation by rivals increases the conditional probability that a decision to adopt will be made. The authors explain this effect by spillovers from technology adoption, rather than the interaction of market concentration and rival precedence. Finally, Hannan and McDowell (1990) investigate more fully what the subsequent impact on market structure is of this technology adoption. As the importance of ATMs in the economy has increased, they find that some firms register some success in using ATMs to attract customers from competitors. However, they find effects on both large and small banks, depending on the local market studied, which implies that the effect on market concentration can be positive or negative.

Saloner and Shepard (1995) build on the analysis of Hannan and McDowell. By including measures of both network size and the number of depositors, they are able to separate the network effect from the scale-economies effect. A recent paper by Gourlay and Pentecost (2002) similarly considers the adoption of teller machines in the U.K. In contrast with findings from more production-focused technologies, they find that experience with the previous vintage of technology has significant effects on adoption. These stock effects are reinforced by learning-by-doing.

The study by Lerner (2004) indicating that financial innovations increased once they became patentable, has already been mentioned. It should come as no surprise that in a highly regulated industry as banking, policy changes are likely to have big effects.

Trautman (1993) investigates another policy dimension – the enforcement of competition law. He provides evidence that permissive sharing laws increase the odds of adoption, which suggests that the antitrust laws may impede the efficient diffusion of the technology. His model also provides evidence that mandatory access laws decrease the odds of adoption for small banks. Both findings suggest that the benefits of such laws in terms of promoting competition in the banking market may be offset by the cost of slower technological diffusion. Finally the model provides evidence that banking markets overlap to a varying degree, which implies that banks compete on the dimensions of price and location. The evidence suggests that mandatory access laws are a more appropriate policy tool when competing banks provide services at similar locations, and permissive sharing laws are more appropriate when competing banks are differentiated by location.

Even though financial innovation has been described as the “life blood of efficient and responsive capital markets,” few quantitative investigations have studied financial innovations and the diffusion of these new technologies. Akhavein, Frame, and White (2005) examine the diffusion of one such technology: credit scoring models for small business lending. Using data for large banking organizations, they use a hazard model to indicate that banking firms with more branches innovate earlier, as do those located in the New York Federal Reserve district, a concentrated banking area. They also find that organizations with fewer separately chartered banks but more branches innovate earlier.

Canato and Corrocher (2004) study organizational change in retail banking. As was already discussed earlier, firm-organization is likely to affect technology adoption decisions. In banking, the distribution network – a bank's branches – is an inherent aspect of the production of its services. The actual organization of the firm cannot be separated from its production technology. In the Canato and Corrocher (2004) paper the focus is how ICT adoption is able to change the organization of the firm by opening up innovative distribution channels. For example, the recent entry of branch-less internet banks in the Canadian market provides a radical change in organization compared to incumbents, which can plausibly be labeled a technological innovation. The authors find that notwithstanding the potential for network rationalization offered by ICT, the number of branches in Italy has increased over time.

4.5.2. Health Care

The health care sector is an important consumer of ICT and much of the patterns discussed earlier will apply. Borzekowski (2002a) studies ICT adoption in hospitals and looks at the effects on the delivery of services (a production effect of technology) as well as the effects on internal organization. Another 'production' effect of IT is on the efficiency of emergency response services, which is analyzed in Athey and Stern (2002). They study an information technology called E911 that links caller identification to a location database and so speeds up emergency response. A significantly improved health outcome can be associated with the new technology, although the authors cannot ascertain that the benefits outweigh the adoption costs, which are sizeable.

A particular feature of the health care industry is that services are financed indirectly, which also has an effect on the adoption dynamics, see Borzekowski (2002b). Similarly, Chou, Liu and Hammitt (2004) are interested in the effect of the introduction of national health insurance on technology adoption of hospitals in Taiwan. They find that a more generous reimbursement system will spur adoption of advanced medical technologies because hospitals engage in quality instead of price competition. They identify the effects from the asymmetric effects the introduction of the national health care system had on private and public hospitals.

Acemoglu, Cutler, Finkelstein, and Linn (2006) investigate a similar issue for the U.S. They look at the effects of the introduction of Medicare in 1965 on subsequent pharmaceutical innovation. For Medicare to have an effect, two conditions have to be met. First, Medicare would have to increase drug spending by the elderly. Second, the pharmaceutical companies would have to respond to the change in market size for drugs caused by Medicare by changing the direction of their research. The empirical work finds no evidence of a first-stage effect of Medicare on prescription drug expenditure by the elderly. Correspondingly, they also find no evidence of a shift in pharmaceutical innovation towards therapeutic categories most used by the elderly.

Under third-party payment, as is the case in virtually all developed economies, hospitals will compete in quality instead of price and a prime channel of quality improvement is embodied technological change. Improved treatment techniques often come embodied in expensive capital equipment. Trajtenberg (1989) studies Computed Tomography Scanners; Baker (2001) and Schmidt-Dengler (2004) investigate the adoption of Magnetic Resonance Imaging (MRI), the next generation technology. Baker (2001) finds evidence that in areas with high managed care penetration, i.e. many health maintenance organizations (HMOs), costs are controlled more effectively, which delays the adoption of MRI. In contrast, Schmidt-Dengler (2004) finds evidence that occasionally hospitals engage in pre-emptive strategies by adopting the MRI technology before their local market can sustain them, simply to obtain a first mover advantage and delay adoption by rival hospitals.

Baker and Phibbs (2002) provide a follow-up study to Baker (2001) and investigate in more detail in what way managed care has influenced technology diffusion in health care. They empirically examine the relationship between HMO market share and the diffusion of neonatal intensive care units. They find that higher HMO market share is associated with slower adoption of mid-level units, but is not correlated with the adoption of the most advanced high-level units. Contrary to the common supposition that slowing technology growth will harm patients, results suggest that health outcomes for seriously ill newborns are improved. The mechanism is that treatment is better in higher-level units and that reduced availability of mid-level units may increase their chance of receiving care in a high-level center, so that slower mid-level growth could have benefited patients.

The effects of information and externalities discussed for technology adoption in general apply equally to technology adoption in a health care setting. Escarce (1996) examines the adoption by general surgeons of laparoscopic cholecystectomy, a new surgical procedure which was introduced in 1989. The paper addresses the informational and cost externalities which may be generated when the first surgeon in a hospital adopts a new procedure. The findings suggest that access to information significantly influenced surgeons' adoption behavior and that externalities in hospitals may have hastened the diffusion of the procedure. Even though individual surgeons make the adoption decision for a new procedure, the fact that they produce their service in a hospital setting, where other surgeons also operate, facilitates learning. Information will be passed around more quickly, network effects can be internalized, information from an experiment by one surgeon can be passed along easily, and learning is more homogenous because several outside factors are explicitly controlled for (all hospital-specific effects are constant). Furthermore, given that competition is in quality not price, surgeons have an incentive to develop a reputation for practicing state-of-the-art procedures which will, ceteris paribus, move the first instance of adoption forward and also hasten the diffusion process.

Even though several of the discussed effects are in line with findings from other industries, they have generated a lot of attention as they suggest that profit maximizing motives and financial incentives are principal drivers also in a sector dominated by not-for-profit firms. Moreover, given that price competition is virtually nonexistent in this sector and that adoption of new technologies is a prime determinant of quality, we would expect the industry to suffer more readily from excessive adoption than from too little. Third-party payment, where the cost of new procedures will only show up indirectly through higher future insurance premiums, provides an additional factor towards excessive adoption.

5. Conclusions

To conclude the survey, we summarize a number of policy conclusions that seem robust over a variety of situations. First, I group a number of studies that have explicitly evaluated specific government interventions. The evidence on the limited success of these interventions confirms a message that came up several times earlier: apparent impediments can rarely be successfully addressed on their own as they are often endogenous outcomes in the industry. This message is elaborated in the final section.

5.1. Positive policy implications

A few studies actually evaluate the effectiveness of government interventions; some were already mentioned in Section 4.1.9 on regulation. For example, Anderson and Newell (2004) analyze technology adoption decisions of manufacturing plants in response to government-sponsored energy audits. Overall, plants adopt about half of the recommended energy-efficiency projects.

Under the assumption that small manufacturers are disadvantaged, several federal and state programs have been created to assist small manufacturers in acquiring and adopting manufacturing innovations. Swamidass (2003) quantifies the extent of technology adoption – and in particular the adoption lag relative to larger firms – in small U.S. manufacturing firms. He uses information from a technology survey that lists 15 distinct technologies that fall into a group of 11 computerized and 4 ‘soft’ technologies.[20] Complete information on the use of these technologies is collected for 1025 plants in surveys for 1993 and 1997, allowing a longitudinal analysis. Apart from documenting absolute and relative adoption rates and covariances with observable characteristics, the study also reveals which manufacturing innovations are in greater need of governmental assistance programs. While small plants are making progress over time in catching up with larger plants in computerized technology use, they are not making similar progress in adopting manufacturing technology innovations in soft technologies. The higher complexity and

[20] Computerized technologies are automated guided vehicles, automated inspection, computer-aided design, computer-aided manufacturing, computer-integrated manufacturing, computer numerical control tools, flexible manufacturing systems, local area networks, materials requirements planning, manufacturing resource planning, and robots. Soft technologies include just-in-time manufacturing, manufacturing cells, statistical quality/process control, and total quality management.

increased risk of these broad technologies is conjectured to be particularly taxing for smaller firms. Providing information to educate small firms about the high returns to investments in manufacturing technologies is expected to have a large pay-off. A continuous improvement theme at some plants has also been found to have high returns as well. Spreading this information is argued to be an important role for public policy. Finally, in mature industries, self-financing the adoption of new technologies is very difficult for small firms and a role for government intervention remains.

Arvanitis, Hollenstein, and Lenz (2002) evaluate the effects of the Swiss government program to promote the diffusion of Advanced Manufacturing Technology (AMT) from 1990 to 1996. Details on the objectives and the implementation of the program are elaborated in footnote 18. Their results are consistent with a positive impact of promotion on adoption of AMT, particularly a more intensive adoption of AMT for firms which did not use AMT when the programme started. This is one instance where intervention is especially effective for the group actually being targeted.

These examples of effective policy interventions stand in sharp contrast with programs aimed at lessening credit constraints, where most support goes to firms that would have adopted anyway and public support to a large extend crowds out private investment.

5.2. Normative policy implications

We close by reiterating a question already raised in the introduction: what can governments do about the impediments to technology adoption that have been identified? Most of the policy implications have already been discussed when the impediments were introduced and we will not repeat them here. A couple of overarching themes that have come up several times include:

- Observable plant characteristics, such as size, age, and composition of the workforce, are often merely correlated with the true impediment to technology adoption and are not ‘causing’ slower adoption. Treating the symptom will not cure the disease.
- Government policies aimed at reducing firm-specific impediments are unlikely to be successful if they do not take into account why the impediments affect some

firms more than others in the first place. As an example, small size has been shown to be strongly negatively correlated with technology adoption. Lowering adoption costs for small plants could boost their adoption, but turn out to be useless in helping those firms succeed any better. Firms that fail to grow often lack the necessary ingredients to be successful in the marketplace, i.e. a good product, high productivity, clever management, etc. The use of advanced technology is unlikely to be a miracle cure for other shortcomings.

- The external environment a firm operates in is often at least as important a predictor of adoption as the firm's own characteristics. Examples include the market structure, competitive conduct, likely impact of the technology, demand uncertainty, etc. As a result it often is no use changing a firm's individual incentives without changing its environment.
- The internal organization of a firm has to accept the new technology and has to adjust to the new technology. Without a culture of change, new technology is unlikely to increase or improve output.
- New technologies are inherently shrouded in uncertainty, especially the potential benefits. Stimulating learning from past experience or other adopters, uncovering complementarities, disseminating information about demand or user costs, identifying possible learning-by-doing effects, etc. are likely to have at least as much of an impact as lowering the (less uncertain) costs of adoption.

Finally, policy interventions are particularly difficult when complementarities exist – a common feature of new technologies; see for example Van Biesebroeck (2006). Any of the weaknesses that are overlooked or impediments to one technology that are ignored, will affect adoption of all complimentary technologies. Social learning or network effects create similar multiplier effects. While this can be dispiriting as we cannot possibly get everything right, the same effects also work in reverse. If a particular impediment for a particular firm cannot be addressed directly, policy can be aimed at complementary technologies or at neighboring firms. Such indirect effects enlarge the range of policy options available. Moreover, once one problem has been addressed, complementarities, learning, and network effects reinforce the positive impacts and the returns to any successful intervention will be that much larger.

Appendix

Table A.1: Summary of technology adoption studies, organized by impediment

Impediments	Section	Study	Country	Period	Technology	Finding
Competitiveness	4.1.1.	Aghion et al. (2005); Baldwin *et al.*(1996) and Baldwin and Rafiquzzaman (1998); Hannan and McDowell (1987); Schmidt-Dengler (2004); Levin *et al.* (1987)	U.K. Canada U.S. U.S. U.S.	1996 1989 & 1993 1971-79 1986-93 1976-82	R&D expenditures 22 advanced manufacturing technologies Automated teller machines MRI Optical scanner	Theory predicts two opposing effects of competitiveness on technology expenditures. Some evidence (e.g. from Canada) suggests the most competitively advanced firms adopt first, but pre-emptive adoption is also documented.
Foreign participation	4.1.2.	Pyke, *et al.* (2002); Veugelers and Cassiman (2004); Baldwin and Diverty (1995); Griffith, *et al.* (2002); Bartolini and Baussola (2001); Vishwasrao and Bosshardt (2001)	China Belgium Canada U.K. Italy; India	N/A 1992 1989 1990-2000 1990-92 1989-93	Manufacturing technologies 'Technical know-how' Manufacturing technologies R&D expenditures and patents Manufacturing technologies International technology purchase agreements	Foreign affiliates are much more likely to adopt technology and spillovers from multinationals to domestic firms are sizeable. However, these differences become smaller if other factors are controlled for.
Plant or firm size	4.1.3.	Rose and Joskow (1990); Swamidass (2003); Thomas (1999); Miravete and Pernias (2006)	U.S. U.S. U.S. Spain	1950-80 1993-97 1979-91 1986-92	Steam-electric generation 15 computerized and 'soft' technologies Computer disk drives Single fire furnace	Large (and productive) firms are significantly more likely to adopt technologies, but to a large extent this represents more frequent adoption opportunities.
Stock effects	4.1.4.	Gourlay and Pentecost (2002); Karshenas and Stoneman (1993); Cabral and Leiblein (2001)	U.K. U.K. U.S., EU, & Asia	1972-97 1981 1990-95	Automated teller machines CNCs Process technology in semiconductor industry	While existing technology use is often important in theoretical models, only small effects of prior technology use have been found.
Internal organization	4.1.5.	Patterson, *et al.* (2003); Bird and Lehrman (1993); Fabiani, Fabiano, and Trento (2005) Hollenstein (2004)	U.S. Japan Italy Swiss	ongoing 1990 2001 2000	Supply chain management Information technology ICT ICT	While both theoretically and empirically the internal organization of the firm matters, no general pattern emerges.

						Changes in firm structure are likely to facilitate adoption. The effect seems largest for ICTs and work both ways, i.e. adoption of ICT will also have an impact on firm structure.
Perception of benefits	4.1.6.	Baldwin and Lin (2002); Baldwin and Rafiquzzaman (1998); Karshenas and Stoneman (1993); Sarkar (1998)	Canada Canada U.K.	1993 1993 1981	22 advanced manufacturing technologies CNCs survey	Perception of higher benefits will obviously boost adoption. With complementarities between technologies or spillovers between adopters, an industry can be stuck in a low adoption state, where perceptions of low benefits are self-fulfilling.
Uncertainty	4.1.7.	Weiss (1994); Hollenstein and Wörter (2004); Faria, Fenn and Bruce (2003); Slade (2001); Luque (2002)	U.S.? Swiss Portugal Canada U.S.	1993? 2002 1990 1980-93 1988-93	Surface-mount technology Internet-based e-commerce Flexible production technologies Mining CNCs, lasers, and robots	Industries or technologies that face higher uncertainty will postpone adoption as the resolution of uncertainty over time generates an option value for waiting. If uncertainty is inherent, reducing irreversibility of investments can speed up adoption rates.
Learning	4.1.8.	Isham (2002); Webster (2004); Fung (2005); Cameron (1999); Zhang, Fan, Cai (2002); Munchi (2004);	Tanzania Australia World India India India	1995 2001-03 1983-97 1975-84 1970-95 1969-85	Fertilizer adoption Innovative activities R&D activities and patenting High-yield seed varieties High-yield seed varieties High-yield seed varieties	Efficiency would be improved if firms could easily learn from past adopters, but learning is hampered by a list of factors. Prior experiences differ and this is hard to control for, even for the firms involved. With firm heterogeneity, it matters who exactly you observe adopting. Given that initial adoption is not random, experience does not easily carry over. Firms do not want their competitors to benefit from their experience.

Regulation	4.1.9.	Gray and Shadbegian (1997); Kerr and Newell (2003); Sakakibara and Branstetter (1999); Lerner (2004);	U.S. U.S. Japan U.S.	1972-90 1971-95 1980-94 1990-02	Pollution abatement Phase down of lead in gasoline Innovative activities and patenting Financial patenting	The literature contains several examples of regulation both helping and hindering technology adoption. Smart regulation can boost adoption and this has happened at times when the natural rate of adoption was 'too slow' in some sense. Regulation can push an industry from one equilibrium to another.
Employee skill level	4.1.10.	López-Acevedo (2002); Zhang, Fan, Cai (2002); Foster and Rosenzweig (2004)	Mexico India India	1992-99 1970-95 1968-82	Advanced manufacturing technologies High-yield seed varieties High-yield seed varieties	Several studies document important interaction effects between the skill level of employees and the propensity for technology adoption. These effects go both ways. Firms with a highly skilled workforce find adoption costs to be lower. On the other hand, adopters often provide complementary training to their workforce to maximize the benefits they can reap from the new technology.
Geography	4.2.1.	Autant-Bernard (2001); Jaffe, *et al.*(1993); Baldwin and Rafiquzzaman (1998); Hu and Jaffe (2001); Bellak (2004); Almeida and Kogut (1997); Griffith, *et al.*(2003); Ivarsson and Alvstam (2005); Bergman, *et al.* (1999)	France World Canada Korea & Taiwan World U.S. U.K. Asia & Latin-Am U.S.	1993-96 1975-89 1993 1977-99 1980-00 1985 1975-98 2001-03 1988-91	R&D input and patenting Patent citations 22 advanced manufacturing technologies Patent citations FDI Design-patent citations R&D expenditures and patenting Technological assistance Lean production systems	Firms are more likely to adopt a new technology from geographically closer neighbors. The actual channels are often left unspecified, but they are often assumed to center around informal meetings by employees of different firms, network opportunities that arise from living in the same areas, more frequent contacts with clients or suppliers that are located close by, etc. This pattern even holds for technologies that are publicly available, e.g. in patents.

Complementarities	4.2.2.	Arora and Gambardella (1990); Hollenstein (2002); Wozniak (1993); Wieser (2005); Van Biesebroeck (2005b); Athey and Stern (2002); Fleming and Sorenson (2001)	U.S., EU, Japan Swiss U.S. World N. Am. U.S. U.S.	1978-88 2000 1976 1970s-1990s 1994-04 1994-96 1990-96	Strategic linkages & agreements ICT Growth hormone implants & feed additives Meta-analysis of R&D expenditures Flexible production 911 information technology Patenting and patent citation	The return to the adoption of one new technology is often increasing in the adoption of other technologies. As a result, firms can be stuck with low use of advanced technologies, because adoption would only be profitable if a range of technologies would be adopted jointly.
Financing	4.3.1.	Dong and Saha (1998); Zeller, *et al.* (1998); Wozniak (1993); Klonner and Gine (2005); Brandt and Zhu (2005); Giudici and Paleari (2000); Cunningham (2004); Canepa & Stoneman (2003, 2004); Bond, *et al.* (2004);	India Malawi U.S. India China Italy Canada U.K. E.U.	1975-85 1990-94 1976 2002-04 1985-92 1997 1992-99 1980-93 1978-89	High yield seed varieties Hybrid maize and cash crops Growth hormone implants & feed additives plastic reinforced fiber boats Technology renovation projects Innovative activities and investment Inventory and capital investment CNC tools Capital investment	This impediment is one of the most straightforward ones that government policy can address. However, the evidence on the importance of credit constraints impeding adoption of new technologies is not as strong as for other forms of investment (particularly capital investments). Moreover, in order to alleviate constraints, governments have to be able to identify credit constrained firms, which is not trivial itself.
Lack of information	4.3.2.	Kremp and Mairesse (2004); Anderson and Newell (2004); Perez-Aleman (2003); Heidenreich (2005); Vanhaverbeke (2001); Schmitz (1999)	France U.S. Chile Germany Belgium Brazil	1998-00 1981-00 1960-99 1990s 1985-95 1967-97	Knowledge management Energy efficiency audits Food processing technology and standard adoption Innovative activities Consumer-oriented networks Production, marketing, design technologies	Government policy can overcome the information constraints that impede technology adoption in two ways. Firms often do not use the available information optimally. Improving internal information processing capabilities often requires outside assistance. In a number of situations, business associations have been successful in achieving information sharing between close-by firms.

Table A.2: Selected summary of technology adoption studies, organized by sector

Sector	Study	Country	Period	Technology
Banking	Hannan and McDowell (1984, 1987, 1990);	U.S.	1971-79	Automated teller machines
	Saloner and Shepard (1995);	U.S.	1972-79	Automated teller machines
	Gourlay and Pentecost (2002);	U.K.	1972-97	Automated teller machines
	Learner (2004);	U.S.	1990-2002	Financial patenting
	Bird and Lehrman (1993);	Japan	1990	Information technology
	Trautman (1993);	U.S.	N/A	ATM regulations
	Akhavein, *et al.* (2005);	U.S.	1997	Credit scoring models
	Canato and Corrocher (2004)	Italy	1990-2002	ICT
Health Care	Athey and Stern (2002);	U.S.	1994-96	911 emergency response
	Baker (2001);	U.S.	1983-93	MRI
	Schmidt-Dengler (2004);	U.S.	1986-93	MRI
	Borzekowski (2002a, 2002b);	U.S.	1987-94	ICT
	Chou, Liu and Hammitt (2004);	Taiwan	1993-98	Advanced medical technologies
	Acemoglu, *et al.* (2006);	U.S.	1965-2000	Pharmaceutical innovation
	Trajtenberg (1989);	U.S.	1972-81	CT scanners
	Baker and Phibbs (2002);	U.S.	1984-96	Neonatal Intensive Care
	Escarce (1996)	U.S.	1989-92	laparoscopic cholecystectomy
Agriculture	Isham (2002);	Tanzania	1995	Fertilizer adoption
	Wozniak (1993);	U.S.	1976	Growth hormone implants & feed additives
	Dong and Saha (1998);	India	1975-85	High yield seed varieties
	Cameron (1999);	India	1975-84	High yield seed varieties
	Zhang, Fan, Cai (2002);	India	1970-95	High yield seed varieties
	Munshi (2004);	India	1969-85	High yield seed varieties
	Foster and Rosenzweig (2004);	India	1968-82	High yield seed varieties
	Zeller, *et al.* (1998);	Malawi	1990-94	Hybrid maize and cash crops
Manufacturing	Baldwin and Lin (2002); Baldwin *et al.*(1996) and Baldwin and Rafiquzzaman (1998); Baldwin and Diverty (1995);	Canada	1989, 1993	22 advanced manufacturing technologies
	Pyke, *et al.* (2002);	China	N/A	Manufacturing technologies
	Brandt and Zhu (2005);	China	1985-92	Technology renovation projects
	Bartolini and Baussola (2001);	Italy	1990-92	Manufacturing technologies
	Fabiani, Fabiano & Trento (2005)	Italy	2001	ICT

Manufacturing (continued)	Vishwasrao & Bosshardt (2001); Swamidass (2003); Luque (2002); Karshenas and Stoneman (1993); Canepa & Stoneman (2003, '04) Faria, Fenn and Bruce (2003); López-Acevedo (2002); Kremp and Mairesse (2004); Perez-Aleman (2003);	India U.S. U.S. U.K. U.K. Portugal Mexico France Chile	1989-93 1993-97 1988-93 1981 1980-93 1990 1992-99 1998-2000 1960-99	International technology purchase agreements 15 computerized and 'soft' technologies CNCs, lasers, and robots CNC CNC tools CNC tools Flexible production Advanced manufacturing technologies Knowledge management Food processing technology and standard adoption
Computer / Semiconductor	Almeida and Kogut (1997); Thomas (1999); Cabral and Leiblein (2001); Weiss (1994); Fung (2005); Giudici and Paleari (2000)	U.S. U.S. U.S., EU, & Asia U.S. World Italy	1985 1979-91 1990-95 1993 1983-97 1997	Design-patent citations Computer disk drives Process technology in semiconductor industry Surface-mount technology R&D activities and patenting Innovative activities and investment
Service sector	Levin *et al.* (1987); Bird and Lehrman (1993); Hollenstein (2002)	U.S. Japan Swiss	1976-82 1990 2000	Optical scanner Information technology ICT
Transportation equipment	Ivarsson and Alvstam (2005); Van Biesebroeck (2005b);	Asia & Latin Am North America	2001-03 1994-2004	Technological assistance Flexible production systems
Bio-technology	Arora and Gambardella (1990);	U.S., EU, Japan	1978-88	Strategic linkages & agreements
Electricity generation	Rose and Joskow (1990)	U.S.	1950-1980	Steam-electric generation
Pulp and paper	Gray and Shadbegian (1997)	U.S.	1972-90	Pollution abatement
Textiles	Vanhaverbeke (2001); Schmitz (1999)	Belgium Brazil	1985-95 1967-97	Consumer-oriented networks Production, marketing, design technologies

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