Innovation, growth theory, and the role of knowledge spillovers

The relationship between innovation and economic growth has been well studied. However, that is not to say that it is well understood. Renowned scholars continue to work with incredibly simplified models of an incredibly complex economy. Consequently, empirical results are usually carefully annotated with caveats noting the limitations of all findings and the great uncertainties that remain concerning fundamental assumptions in the field.

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Clearly though, the immense complexity of this subject has not quelled scholarly interest in this topic, but rather has increased it. This topic has generated numerous studies, which have been synthesized into many books (Griliches 1998; Nelson, 1996; Mowery and Rosenberg, 1989; Helpman, 1998; Malecki, 1997; Scherer, 1999).

A theoretical link between innovation and economic growth has been contemplated since at least as early as Adam Smith (1776). Not only did he articulate the productivity gains from specialization through the division of labour as well as from technological improvements to capital equipment and processes, he even recognized an early version of technology transfer from suppliers to users and the role of a distinct R&D function operating in the economy:

"All the improvements in machinery, however, have by no means been the inventions of those who had occasion to use the machines. Many improvements have been made by the ingenuity of the makers of the machines, when to make them became the business of a peculiar trade; and some by that of those who are called philosophers or men of speculation, whose trade it is not to do anything, but to observe everything; and who, upon that account, are often capable of combining together the powers of the most distant and dissimilar objects. In the progress of society, philosophy or speculation becomes, like every other employment, the principal or sole trade and occupation of a particular class of citizens… and the quantity of science is considerably increased by it."[1]

Although the relationship between innovation and growth had been articulated at an intuitive level for some time, innovation was not introduced into formal economic growth models until 1957 (Solow, 1957). Robert Solow, a professor at MIT, was awarded a 1987 Nobel Prize in Economics for this and related work. Like scholars before him, he defined growth as the increase in GDP per hour of labour per unit time. He carefully measured the fraction of this growth that was actually attributable to increases in capital, such as investments in machinery and related equipment, since the theory of the day was that capital accumulation was the primary determinant of growth. However, capital accumulation accounted for less than a quarter of the measured growth. Solow's insight was in attributing the remainder of the growth, the majority share, to "technical change." The magnitude of the residual calculated in this empirical study placed the role of innovation in economic growth squarely on centre stage, where it has remained for the past half century.

Since Solow's contributions, the relationship between innovation and growth has been modeled in increasingly sophisticated ways. Perhaps the most notable recent advances came from Lucas (1988) and Romer (1986, 1990), who emphasized the concepts of human capital and knowledge spillovers, respectively. Following the recent idea of distinguishing human capital, which is developed by investments in education and training, from physical capital, Lucas modeled human capital with constant rather than diminishing returns, thus offering useful insights into the critical role of a highly skilled workforce for long-term growth. Romer endogenized innovation in the growth model by introducing knowledge spillovers, which resulted in deep implications for how scholars think about growth.

The following is a gross simplification of how the Romer model works. Firms engage in R&D because they expect it will be profitable. In other words, firms allocate funds to R&D as long as the expected payoff (return on investment, or "ROI") from R&D at the margin is higher than for any other allocation of those resources. This investment in R&D results in the creation of two types of knowledge, that which is appropriable and that which is not. Appropriable knowledge refers to knowledge the firm can utilize itself, exclude others from using, and generate profits from. Knowledge that is not appropriable has the properties of a public good; it is non-rivalrous (use by one firm does not preclude use by another) and non-excludable (it is difficult to prevent others from using). The more knowledge there is, the more productive R&D efforts using human capital are. So, when firms conduct R&D, they apply human capital to the stock of knowledge for profit-maximizing purposes. In the process, however, the firm unintentionally contributes back to the increasing stock of knowledge. This unintentional contribution is referred to as a knowledge spillover.

The implications of this model are increasing returns to growth from investments in human capital and R&D due to knowledge

[1] While this quote is from the text of Adam Smith, Scherer (1999) is acknowledged for noting the relevance of this passage to the topic considered here.

spillovers. This is because the more human capital that exists in an economy, the more value that economy can derive from the stock of public knowledge through R&D efforts, which further raises the value of conducting R&D. As a result, the economy engages in more R&D, which in turn makes further contributions to the stock of knowledge spillovers; this argument continues in a virtuous circle. This model is based on the assumption that profit-seeking firms will engage in R&D for selfish reasons, since they can appropriate some of the value from the knowledge they create. Most economists argue that a role also exists for the public funding of some types of R&D, particularly basic research that is often very hard for any single firm to appropriate, since the resulting knowledge spillovers are valuable to the overall economy and would otherwise suffer from under-investment.

This explains why the concept of knowledge spillovers is central to our thinking about innovation and growth. So, in the next section, highlights from recent work on knowledge spillovers are reviewed.

Knowledge spillovers and the appropriability problem

From the above discussion, it may not be clear why investments in human capital or local R&D have any relevance to the economic growth of any particular country, such as Canada. If knowledge spillovers are a public good, why does it matter which country produces them? In fact, might it not be optimal for a particular country to "free ride" on the efforts of other nations? At the same time, the concept of knowledge spillovers as a public good may seem inconsistent with the evidence, given the variety of growth rates across open economies. Why haven't all countries converged towards equal prosperity if knowledge spillovers are freely available?

There may be many path dependency reasons for this (i.e., differences in initial conditions), but, for the purposes of this paper, the focus is on human capital and tacit knowledge. Human capital refers to the level of education and training in an economy. Tacit knowledge refers to knowledge that is difficult to codify.

For example, consider the knowledge spillovers generated by a firm that conducts research in Toronto. Some fraction of the cities around the world will possess local human capital that has the capacity to benefit from this research by examining the firm's new product or by reading the firm's patents or journal publications. However, part of the knowledge that was generated from the research may not be easily inferred from examining the product or simply communicated through written documents, even if the firm is not intentionally keeping it secret. This is the tacit knowledge that is passed from one engineer to another only through direct interaction. As a result, it may be the case that other firms in Toronto or whose engineers visit Toronto benefit more from the spillovers generated by the firm in this city than those at a distance. Many scholars argue that tacit knowledge is "sticky" and remains geographically localized. This has significant implications for innovation and its impact on regional economic growth, since this public good, a key ingredient to growth, is obtainable at a much lower cost by local firms.

Following are brief surveys of two literature streams related to knowledge spillovers. The first examines the degree to which spillovers are geographically localized and explanations for why this might be so. The second examines the characteristics of firms that enable them to utilize knowledge spillovers. The ability of a firm to exploit knowledge spillovers is referred to as its "absorptive capacity."

Localized knowledge spillovers

Most papers in this stream of research measure the variance in levels of knowledge inputs and associated outputs and examine this relationship across geographic space. The inputs and outputs considered vary from study to study, as does the geographic unit of analysis. Jaffe (1989) relates the input "federal research funding" to the output "new patents issued" and examines the variance in this relationship across geographic space at the state level. Jaffe *et al* (1993) relate the input "original patents" to the output "patents that cite the original patents" and examine the variance in this relationship across geographic space at the city level. Audretsch and Feldman (1996) relate the input "local university research funding" to the output "local industry value-added" and examine the variance in this relationship across geographic space at the state level.

Zucker *et al* (1998) relate the input "number of local research stars" to the output "number of new local biotech firms" and examine the variance in this relationship across geographic space at the economic region level. Branstetter (2000) relates the input "scientific publications from the University of California" to the output "patents that cite those papers" and examines the variance in this relationship across geographic space at the state level. Agrawal (2000) relates the input "hours of interaction with the MIT professor associated with a particular patented invention" to the output "likelihood or degree of success in commercializing the invention" and examines the variance in this relationship across geographic space in terms of distance measured in miles. Key findings reported in these papers are described briefly.

Results from Jaffe's 1989 study indicate that patents occur in those states where public and private knowledge-generating inputs are the greatest. Even after controlling for industrial R&D, the results indicate that the knowledge generated at universities spill over for higher realized innovative output. The author also reports results suggesting that university research appears to increase industry R&D, which in turn increases the production of patents.

Jaffe *et al* investigate the degree to which knowledge spillovers are geographically localized. They conduct this experiment by examining patent citations of patents. Specifically, they compare probabilities of patents citing prior patents that are associated with inventors from the same city with a randomly drawn control sample of cited patents. The authors report results suggesting that the citations are significantly more localized than the controls after adjusting for organizational types, such as universities. These results hold when the data is aggregated for analysis at higher geographic levels.

Audretsch and Feldman report results that indicate the relative economic importance of new knowledge to the location and concentration of industrial production. Even after controlling for the geographic concentration of production, the results suggest a greater propensity for innovative activity to cluster spatially in industries in which industry R&D, university research, and skilled labour are important inputs.

Zucker *et al* report results indicating that the number of local stars and their collaborators is a strong predictor of the geographic distribution of biotech firms in 1990. Importantly, these results persist when controls are added for the number of top-quality universities in the region and the number of faculty with federal support in the region.

Branstetter's results suggest that distance does matter, or at least regions matter. While being in the same state has a statistically significant impact on the probability of a citation, linear distance measured in miles does not. The results also suggest that the temporal link between academic science and patented innovation is short. The modal lag in the raw data is only two years, indicating that it is recent science that is a driving force behind patenting.

Agrawal examines the importance of geographic distance and direct interaction between university inventors and company scientists to the successful transfer and commercialization of patented university inventions. This study supports the hypothesis that geographic distance, measured in miles between MIT and the licensee, has a negative effect on the commercial success of the licensed invention. This effect becomes statistically insignificant when a control for direct scientific interaction, measured in numbers of hours, is introduced. The interaction explanatory variable does have a positive effect on both the likelihood and degree of commercial success.

The concepts of localized knowledge spillovers and absorptive capacity are closely related. Whereas the spillover literature is focused on the variance of the production function over distance from the R&D source, the absorptive capacity literature is focused on the variance of the production function across firms that vary in their organizational design. A brief summary of a few of the most important papers on absorptive capacity follows.

Absorptive capacity

There is a small but growing literature concerning the organizational design of firms that influence their ability to utilize knowledge spillovers. This branch of research originates from a pair of papers by Cohen and Levinthal (1989, 1990) that introduce the concept of "absorptive capacity"[2] and argue that a firm's ability to utilize knowledge spillovers for its own commercial gain is a function of its investment in R&D. Cockburn and Henderson (1998) build on this notion, but add that the degree to which firms are "connected" is also important for utilizing knowledge spillovers. Lim (2000) restructures the above two concepts and argues that the absorptive capacity of firms is primarily a function of its connectedness, of which its investment in R&D is just one of several components. Finally, Zucker *et al* (2000) investigate the importance of connectedness to firms by examining their location decisions relative to star university scientists. These papers are now described.

Cohen and Levinthal introduce and develop the concept of absorptive capacity and argue that this characteristic of the firm is strongly related to its prior related knowledge generated by in-house R&D.

The authors report results that support their two predictions. First, in the case of technological opportunity, the estimated coefficients for the impact of the applied sciences on R&D intensity are generally lower than those for the basic sciences, since the basic sciences are more relevant (of higher quality) and this knowledge has a more positive effect on R&D intensity. Second, the effect of increasing appropriability on R&D intensity is shown to be significantly greater in those industries in which the applied sciences are more relevant to innovation than the basic sciences. The authors conclude that these results support their hypothesis that R&D investments create a capacity to assimilate and exploit new knowledge.

Cockburn and Henderson argue that while investments in in-house R&D are necessary for firms to develop their absorptive capacity to utilize knowledge spillovers, this alone is not enough. Firms must be connected to the open science community by being actively involved in sharing research results (publishing) as well as engaged in research collaboration. The authors interview research scientists and managers from both the public and private sectors that both confirm the importance of absorptive capacity in the classical sense and identify three additional factors perceived as being important for conducting leading-edge research within the firm. These include: 1) recruiting the best people, 2) rewarding researchers on the basis of their standing in the public rank hierarchy, and 3) encouraging them to be actively engaged with their public-sector counterparts.

The authors address two related questions with their quantitative analyses concerning the concepts of connectedness, the organization of internal research, and research productivity. Their results indicate a positive relationship between connectedness and research productivity, which is arguably the most interesting finding reported in this paper.

Lim picks up from Cockburn and Henderson and argues that not only is connectedness important but it is in fact the main ingredient for creating absorptive capacity. Internal R&D is but one mechanism to foster connectedness, and it in turn generates absorptive capacity. The author identifies three additional mechanisms for fostering connectedness, including: 1) cultivating university relationships by way of sponsoring research, collaborating with faculty, and recruiting graduate students, 2) participating in research consortia, and 3) partnering with other companies that do related scientific research. The key contribution of this study is the finding that firms are able to acquire and exploit externally generated scientific knowledge without conducting in-house R&D, but instead by being connected to the scientific community in other ways.

[2] The concept of absorptive capacity is prevalent throughout the knowledge transfer literature. This refers to a firm's ability to recognize, assimilate, and apply new scientific information for its innovation and new product development.

Zucker, Darby, and Armstrong investigate the effect on the performance of the firm of star university scientists who either left tenured positions to found firms or who remained in the university but established tight working relationships with their colleagues in private industry. The primary result of this research is that the number of star scientists who are tied to the firm, either linked or affiliated, have a positive and significant effect on the productivity of the firm in all three major stages of research and product development.

Given the importance of knowledge spillovers and absorptive capacity to the issue of innovation and growth, these papers offer a useful point of departure for further investigation.

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