Diffusion of Technology

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The technology of a firm or country determines the efficiency with which inputs are mapped into outputs. Technological change may result in the ability to produce entirely new products, or it may allow an existing product to be produced with fewer inputs. This process has long been viewed as central to economic growth. The question of whether or not there is convergence across firms and countries raises issues related not only to the process of technical change, but also to the diffusion of technology. Beginning in the late 1950s, economists have formalized their thinking of how such technological knowledge diffuses from one economic entity to another. The early efforts were primarily directed to understanding firms' technology adoption decisions that often yield an S-shaped diffusion pattern over time. During the last 15 to 20 years, a vibrant literature has emerged in which the issues addressed are considerably broader, and where much more emphasis is given to seeking high-quality empirical evidence.

A firm's technology and its productivity are closely related, and the two are identical if technology is identified with total factor productivity, an approach frequently taken since the 1950s. The development of models of endogenous technical change in the early 1990s represented a step forward in that the R&D resources devoted to innovation were separated from the new technological knowledge itself. For example, consider the technology production function

$$(1) \qquad \dot{N} = \eta N^{\lambda} H_N \ ,$$

where η and λ are parameters, $\eta, \lambda > 0$. The term H_N denotes the skilled-labor resources devoted the R&D, which according to equation (1) lead to a flow of new technological knowledge of $\dot{N}$. A higher level of R&D produces a higher level of technology, N, and that in turn can be shown to result in higher productivity.

According to equation (1), a higher stock of existing technological knowledge facilitates innovation. This stock of technological knowledge will rarely be entirely self-produced, so that (1) typically involves the diffusion of technology—diffusion between different persons, firms, and/or countries. Technology is sometimes purchased or licensed in a market transaction, but due to asymmetric information and other problems in the market for technology, non-market transactions in form of technological externalities, called knowledge spillovers, are much more important.

What are the nature and the size of these knowledge spillovers? Since technological knowledge is non-rival, such externalities can in principle benefit many economic agents.

A useful benchmark is the complete diffusion of technology, which describes the case where technological knowledge created anywhere in the world is available in all countries worldwide immediately. This could underlie the assumptions of common-to-all and free technological knowledge of neoclassical growth theory. Clearly, this is not true in reality, where the diffusion of technology is gradual and uneven.

Why? First of all, acquiring technology involves making complementary investments, and the equilibrium choice for such investments often implies that not all technology diffuses. For instance, in Keller's (1996) model, international trade enables domestic producers to raise productivity by importing specialized foreign intermediate goods. Since these goods embody foreign R&D investments, this means the diffusion of technology from one country to another. For this imported technological knowledge to trigger domestic innovation, however, additional investments are necessary. According to Keller (1996), these investments are in terms of additional training of workers so that they have the skills to manufacture products according to new blueprints. In addition, domestic innovators may have to invest resources into reverse engineer the foreign intermediate goods in order to fully comprehend the underlying foreign technological knowledge.

Second, another major determinant of the firm's decision to acquire the existing technology and innovate is the degree of product market competition. For example, in early Schumpeterian endogenous growth models, a higher degree of product market competition leads to lower monopoly profits and thus to a lower rate of innovation. More recent work by Aghion et al. (2001), for example, shows that if technological laggards must first catch up with the leading-edge technology before battling for technological leadership in the future, the overall effect of more product market competition may be positive. The reason for this is that even though more competition means lower monopoly profits, now technological leaders also have an incentive to innovate to avoid competition with technological laggards, and if the latter effect is strong enough, product competition has a positive effect on technology diffusion and growth.

Third, there is no complete diffusion because it is simply not in the interest of the original creator of the technology, since his market for the technology would shrink if there were additional suppliers. In some cases, innovators obtain a patent that provides government-sanctioned protection of economic interests for a limited period of time in exchange for release of the technological information. Another strategy on the part of the original innovator is to use a varying amount of resources to keep the technological knowledge secret. At the same time, studies show that it often does not take more than two years until new technology becomes publicly available.

Another, probably the most important reason of why knowledge spillovers are limited is the fact that only the broad outlines of technology are codified—the remainder is the 'tacit' part of the knowledge. A person who is engaged in a problem-solving activity can often not fully define (and hence prescribe) what exactly she is doing. Along these lines, technology is only partially codified because it is impossible or at least very costly to fully codify it. For technology diffusion to occur completely, it may be necessary that the person who learns about the new technology can observe another person in the process of applying the technology. Even if this can be dispensed with, person-to-person contacts will generally be beneficial to the diffusion of technology.

Research has now turned to the essential task of assessing the importance of these processes empirically. As an intangible, technology is intrinsically difficult to measure, and economic data is hard to come by. This is even more so the case for the diffusion of technology, the non-market effects caused by technological knowledge. The main approach for quantifying technical change has been to study the relationship between R&D investments and productivity (Griliches 1979). For example, Keller (2002a) estimates

(2) $tfp_{it} = \beta s_{it} + X'\gamma + \varepsilon_{it}$, i = 1,…, I, and t = 1,…, T,

where tfp_{it} is log total factor productivity in industry i at time t, s_{it} are industry i's cumulative R&D investments (in logs) in period t, X is a vector of other observed determinants of productivity, and the error ε_{it} picks up unobserved effects. The parameter β, estimated in Keller (2002a) at $\beta = 0.15$, measures how R&D investments translate into higher productivity, thereby implicitly capturing the rate of technical change.

This approach is attractive since R&D spending is the main cause of technical change, and data on R&D expenditures are relatively easy to collect and compare across units (firms, industries, and countries). A drawback is that measuring technical change this way requires an estimate of β. This can be complicated if productivity is badly measured, R&D is endogenous, or unobserved determinants on productivity are important, as in practice is often the case. Recent applications of instrumental-variable and control-function approaches have shown much promise in addressing the major estimation concerns (see Gong and Keller 2003). Patents are an alternative measure of technology, and it has the advantage that patent data is available for a broader set of countries and a longer time horizon than data on R&D is (Jaffe and Trajtenberg 2002). While patent counts are an imperfect measure of technology because the distribution of patent values is extremely skewed, recent work using citations-weighted patent data has addressed this point since citations to a particular patent are a plausible indicator of its value. At the same time, patents cannot capture more than the codified part of technological knowledge, apart from the fact that across industries and firms, the prevalence of patenting varies strongly for reasons that are difficult to fully address.

Technology spillovers, as the major form of technology diffusion, are mainly analyzed by extending equation (2) above to estimate as well the effects of R&D investments conducted elsewhere. For example, in addition to the effects of own-industry R&D, Keller (2002a) estimates the effects of R&D in other domestic industries (s_{it}^{do}), as well as those of R&D in the same and other foreign industries (s_{it}^{f} and s_{it}^{fo}, respectively):

(3) $tfp_{it} = \beta_1 s_{it} + \beta_2 s_{it}^{do} + \beta_3 s_{it}^{f} + \beta_4 s_{it}^{fo} + \widetilde{X}'\gamma + \varepsilon_{it}$.

In this framework, the estimates of β_1, β_2, β_3, and β_4 determine the relative strength of intra- versus inter-industry and domestic versus international technology diffusion. For his sample of eight large OECD countries, Keller (2002a) finds that intra-industry effects dominate inter-industry spillovers, and that about 25% of the total effect is due to international technology diffusion.

Other interesting approaches have employed multi-country extensions of recent models of endogenous technical change that include international technology diffusion (Eaton and Kortum 1999). Because here the economic environment is fully specified, it is straightforward to simulate a model and perform interesting policy experiments. At the same time, typically there is little data on technology diffusion employed in the econometric estimation of these models. Consequently, the model's structure has a great influence on the results, while the implications for the diffusion of technology are not clear.

One major finding has been that the diffusion of technology is geographically localized, both domestically as well as internationally. For example, Keller (2002b) studies international technology diffusion between the G-5 countries (the US, Japan, Germany, France, and England) and nine smaller OECD countries by estimating

$$(4) \qquad tfp_{it} = \beta\left[s_{it} + \sum\nolimits_{j \in G5} \exp\left(-\delta\, Dist_{ij}\right) s_{jt}\right] + X'\gamma + \varepsilon_{it} \text{ ,i = 1,…, I, and t = 1,…, T.}$$

Here, $Dist_{ij}$ is the geographic distance between country i and G-5 country j. The parameter δ determines the extent of geographic localization: the higher is δ, the stronger is the degree of the localization of technological knowledge, while if $\delta = 0$, international technology diffusion is complete in the sense that geography has no impact whatsoever. The geographic reach of technology spillovers is a critical determinant of the cross-country income distribution, since global spillovers favor income convergence while local spillovers lead to income divergence. Keller's (2002b) results for the years 1970 to 1995 strongly reject the null hypothesis of complete diffusion. Instead, he estimates that with every additional 1,200 kilometers of distance, there is a 50 percent drop in technology diffusion. The results imply that the benefits of being located next to major technology producers are substantial, highlighting the danger of being left behind for isolated areas.

While distance still shapes technology diffusion in a major way, there is also evidence that recently, geography's grip on technology diffusion has weakened. Keller (2002b) estimates that the size of the δ parameter in equation (4) has fallen substantially from the late 1970s to the 1990s, consistent with the idea that innovations in information and communication technologies have led to a major improvement in technology diffusion.

Such improvements in countries' abilities to draw on international innovations also imply that the ultimate sources of domestic productivity growth lies increasingly abroad. This is especially true for medium-sized and small countries, where the contribution of foreign technology to domestic productivity growth often exceeds 90 percent. At the same time, because successful technology diffusion requires complementary investments in terms of adaptive R&D and/or human capital, domestic activities have a significant impact on the ease of technology diffusion.

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