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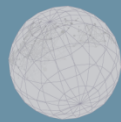
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Evolving Technological Capabilities of Firms; Patterns of Complexity, Divergence, and Stagnation in Corporate Invention

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Introduction

Innovation is what drives competitive advantage of firms, and productivity growth in the economy as a whole. Firms draw on the globally available stock of technological knowledge to innovate. To remain competitive, firms have to keep developing and acquiring new knowledge. However, since the late 1990s the productivity growth has slowed markedly for many of the world's largest economies. While there are many more researchers and engineers, in more locations around the world than ever before, and much more money is spent on technological research, the pace of innovation, the production of new knowledge that will feed the pipeline of future progress, appears to be slowing (*OECD Compendium of Productivity Indicators 2016*, 2016). Much work before now has found that slower technology growth is the main driver of this productivity paradox (Brynjolfsson, 1993; Cowen, 2011; Gordon, 2016). However, (Dan Andrews, Criscuolo, & Gal, 2016) showed that the top ("frontier") firms in OECD member countries have continued seeing productivity increases while the others (the "laggards") have not, contributing to a growing productivity divergence between the top and the bottom. The study also suggests that the difference in the ability of firms to develop new technological knowledge is an important reason for this pattern of divergence (Andrews, Criscuolo, & Gal, 2016). However, they did not study the knowledge base of the firms, which could provide information about how the changing technological portfolio of firms drives performance.

It is remarkable how little is actually known about the characteristics of the knowledge base of innovative firms that operate at the technological frontier. In this paper, we wish to address this gap in our understanding and answer the question how the characteristics of the technological knowledge base of firms explains their innovative performance, comparing frontier and non-frontier firms. For the period 2000-2010, we first establish the composition of the global patent portfolio of the world's top 2000 R&D performing companies. Second, we

study how patterns of divergence among firms can be explained by the diversity, complexity and growth of the technological knowledge base of firms.

The novel contribution of this paper that we provide insights in the underlying patterns of technological development. More specifically, this study uses the Corporate Invention Board (CIB) dataset. This sample of patents analysed for constructing the global map of technology encompasses all priority patents (over 6 million documents) applied for worldwide between 2000 and 2010 by the 2400 largest private R&D performers – i.e., the corporations monitored in the EU Industrial R&D Investment Scoreboard. CIB represents a significant share of private R&D investments as the industrial corporations included in the project account for 80% of world total private R&D (Alkemade, Heimeriks, Schoen, Villard, & Laurens, 2015).

Theory

The starting point of our analysis is that technological progress relies on recombinant innovation (Arthur, 2007; Malerba & Orsenigo, 1996), the recombination of existing technologies where firms combine prior art with their own ideas to form new patentable technologies - now more than ever (Wuchty, Jones, & Uzzi, 2007). Because of bounded rationality, search for new technological knowledge is highly uncertain. As a result, firms tend to draw on knowledge acquired in the past, which provides opportunities but also sets limits to what can be learned (Atkinson & Stiglitz, 1969). As (Cohen & Levinthal, 1989) argued, agents are more likely to understand, absorb and implement external knowledge when it is close to their existing knowledge base. This also implies that knowledge is widely dispersed among many heterogeneous agents, and that the process of knowledge creation heavily depends on combining different capabilities of agents (Nooteboom, Van Haverbeke, Duysters, Gilsing, & van den Oord, 2007).

While the global stock of available technological knowledge keeps on expanding, it has been suggested that all the ‘low hanging fruit’ has been picked (Cowen, 2011). As a consequence, it becomes increasingly complex to develop new technological knowledge and to bring together the necessary skills and capabilities required to bring about new technological combinations (Chesbrough, 2003; Jones, 2009).

In the Schumpeterian framework of innovation, technological change is considered as successful new combinations of existing technologies. Furthermore, technological knowledge can be considered as an interconnected set of qualitatively different ideas (Kauffman, 1995; Saviotti 1998). In cognitive theory, such a depiction has led to stress the trade-off that exists between diversity and similarity: On the one hand, organizations who share a greater overlap in terms of technological competences may find it easier to communicate with one another, facilitating learning. On the other hand only organizations that possess non-overlapping competences and technological knowledge can actually offer something new to be learnt. As a matter of fact, a too strong overlap in competences might even lead to cognitive lock-in (Nooteboom, 2000). This trade-off suggests that from an innovation perspective there is an optimal cognitive distance (Nooteboom 2007). A measure technological distance can thus contribute to identify the building blocks of technological evolution.

The path-dependent evolution of knowledge involves the dissemination of results through patents which translates corporate research into a global knowledge base where codified technologies can be utilised by others. Thus, technological knowledge production is a global, collective and distributed system in which firms are positioned with respect to the global knowledge base (Boschma, Heimeriks, & Balland, 2014; Cohen & Levinthal, 1990; Cohen &

Levinthal, 1989; Heimeriks & Boschma, 2014). Technological knowledge is differentiated among firms, given that it is specific to the context in which it is created. Creating new knowledge does not occur in abstraction from current abilities. Rather, new learning, such as innovations, are products of a firm's combinative capabilities to generate new applications from existing knowledge (Kogut & Zander, 1993).

When locally embedded knowledge is combined in novel ways with codified and accessible external knowledge, new knowledge and ideas can be created (Heimeriks and Boschma 2014). Consequently, the creation of new knowledge is expected to be characterised by a path-dependent process of branching: new knowledge is developed from existing knowledge, skills and infrastructures in relation to global knowledge base.

We also expect that, as firms specialise in particular competences, these specialisations will offer opportunities for further improvements in similar technological fields and discourage the creation of knowledge on technologies unrelated to their existing technological routines and capabilities (Boschma et al. 2014). Thus, Hypothesis 1 states that the entry of technologies of firms can be explained by their relatedness to the existing technological portfolio. Related technologies are more likely to enter the portfolio of a firm than unrelated technologies.

Many observers fear we experience a productivity paradox of slower technological development. Wuchty et al. (2007) and Jones (2009) emphasise that incremental recombinant innovation is growing in relevance due to the growing burden of knowledge, which requires greater investments in human capital and team work and a greater reliance on reusing existing ideas in new ways. Technological knowledge becomes obsolete more quickly than before in a process of creative destruction because new technological developments make knowledge of older technologies redundant. Furthermore, it becomes increasingly difficult to bring together the necessary skills and capabilities required to bring about new technological combinations (Jones, 2009). Nowadays, a great variety of knowledge and skills is needed to achieve real innovations. According Chesbrough (2003), it is simply more difficult for companies to innovate: the rising costs of R&D, the increasingly shorter product lifecycles, more mobile workforce, increasing globalization and the erosion of market positions.

In this context, Gordon (2012) argues that the recent productivity slowdown is a permanent phenomenon because the types of innovations that took place in the first half of the 20th century (e.g. electrification) are far more significant than anything that has taken place since then (e.g. ICT), or indeed, likely to transpire in the future. By contrast, technological optimists tend to argue that the underlying rate of technological progress has not slowed and that the ICT revolution still has a long way to run (Brynjolfsson and McAfee, 2011; Mokyr, 2014).

At the same time, the potential for innovation is increasing rapidly. More technological building blocks become available. Technological development applies positive feedback since successful inventions resulting from one stage of evolutionary progress can potentially be used to create the next stage. The international production and transmission of know-how, knowledge and technological expertise is growing and it is increasingly important in the world economy (Archibugi, 2003; OECD, 1998). More companies and countries produce technological knowledge (Alkemade et al., 2015). Furthermore, codified information is more easily transferable across geographical space through the Internet, digital patent databases, scientific journals, international conferences, mobility of researchers and through foreign direct investment by multinational corporations (David & Foray, 2002; Heimeriks &

Vasileiadou, 2008). New opportunities for increasingly complex technological developments are now opening to benefit from the globally available stock of technological knowledge.

More generally, the growth of complexity can be expected to be driven by the co-evolution among firms and the growing technological knowledge base to which firms try to stay adapted: as any of these become more complex in order to cope better with the diversity of threats and opportunities offered by the ecosystem formed by the others, the others too will have to adapt by becoming more complex, thus triggering development towards more complexity. We expect that companies thus require an increasingly complex stock of knowledge in order to remain competitive. This trend may be reinforced by the fact that the knowledge ecosystems themselves tend to become more complex over time, as technological diversity increases, together with the linkages or dependencies between technologies.

Data and Methods

The patent system grants a firm monopoly rights over an idea for a fixed period, with the aim to provide monopoly rents to improve incentive to innovate (Schumpeter, 1943), because there will be under-investment due to the public goods nature of ideas (Arrow, 1962; Nelson, 1959).

Our methodology follows the ‘product space’ framework, which integrates network science with macroeconomic theories in order to understand the uneven development of countries (Hidalgo, Klinger, Barabasi, & Hausmann, 2007). This framework develops a two-mode network approach of the economy constructed from country-product pairs. In this paper, we apply the product space framework to technology dynamics, and our two-mode network is based on pairs of firm–technological field constructed from CIB patents in the period 2000–2010.

The quality of any measure of distance depends on the quality of the underlying classification. We use patents as our measure of technological development. While patents are considered an intermediate innovation indicator, data availability and the possibility to capture also emerging technological fields explain their widespread use in the study of technological change (Archibugi and Pianta 1994; OECD 2009). In order to overcome some of the difficulties associated with the use of patents as an indicator for technological change, we use a subset of all patents for the construction of the global technology map.

Constructing the global map of technology

More specifically, this research uses the Corporate Invention Board (CIB) dataset (Alkemade et al., 2015). This sample of patents analysed for constructing the global map of technology encompasses all priority patents (over 6 million documents) applied for worldwide between 1986 and 2005 by the 2400 largest private R&D performers – i.e., the corporations monitored in the EU Industrial R&D Investment Scoreboard. The CIB complements the “Industrial R&D Investment Scoreboard” produced annually by European Commission’s Institute for Prospective Technological Studies. The industrial R&D Investment Scoreboard analyses the performances of the 2000 industrial companies (1000 based within the European Union, 1000 outside) with the highest annual R&D investments. CIB represents a significant share of private R&D investments as the industrial corporations included in the project account for 80% of world total private R&D.

While patent classification systems provide a starting point for identifying patents that belong to a specific technological domain, they do not constitute a classification of technological fields (OECD 2009). In order to overcome this problem, we developed an original classification of technology that distributes all inventions in 401 non-overlapping classes. This classification is based on the well-established WIPO hierarchical classification that distinguishes, at its finest aggregation level, 35 technological fields, these 35 fields, being grouped in 5 technological domains. The global technology map depicts how these technological fields are connected.

The distance between areas of technology is based on the analysis of the co-occurrence of IPC codes assigned to individual patent documents. The more often a code is assigned to patent documents within one area together with codes from another area, the stronger the relationship between those codes and the shorter the (technological) distance between the technological areas to which these codes belong. The global technology map thus provides a “bottom up” measure of the technological distance between different technological fields.

Firm level variables

The distances between technological fields can then be used to analyse the role of technological relatedness in the development of firm-level knowledge bases. More specifically we use the density index developed by Hidalgo (2007). This index has recently been applied in several studies analysing the diversification strategies of countries, regions and cities (REFS), in this paper we examine whether similar processes drive the knowledge base developments of multinational companies. More specifically, we calculate the relatedness of the knowledge base of firm f to technological field k $density_{kf}$ by dividing the sum of technological relatedness between technological field k and other technological fields that are already part of the firm's knowledge base by the sum of technological relatedness between technological field k and all other technological fields.

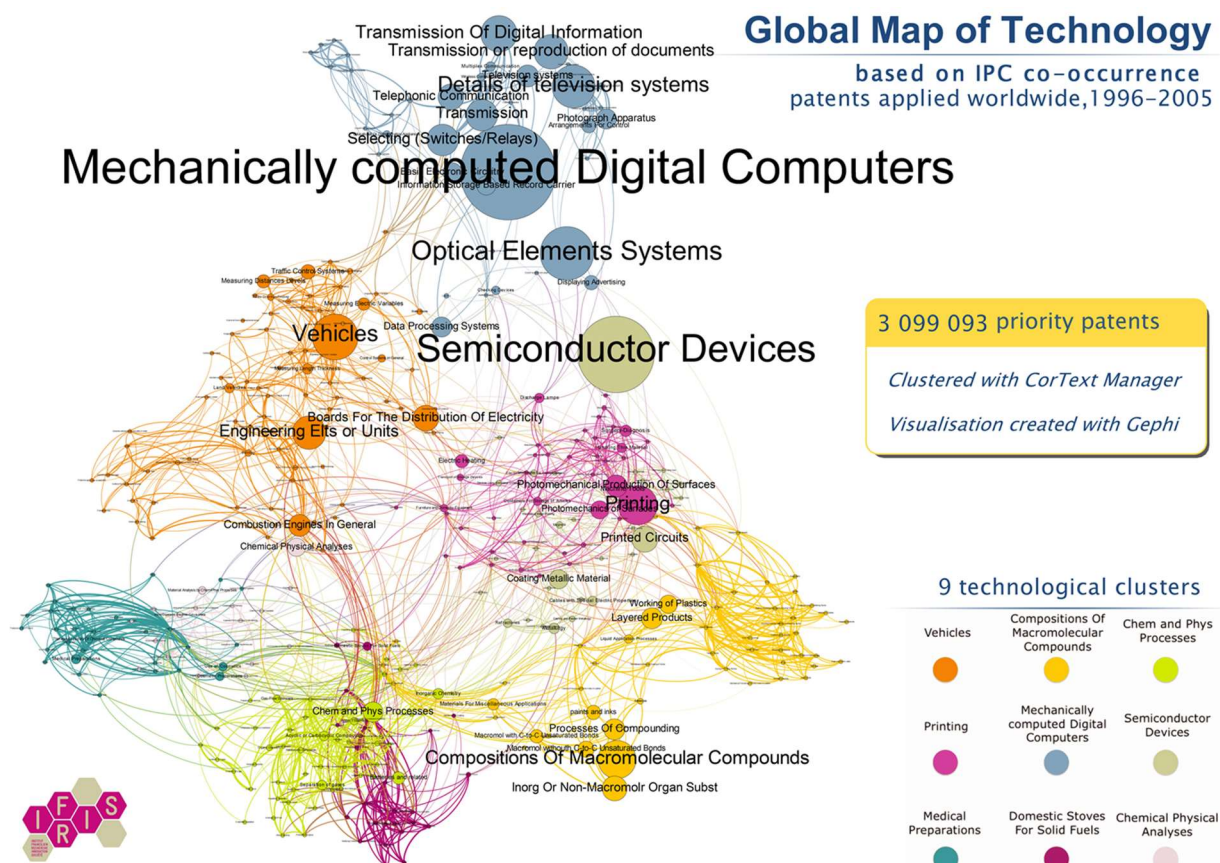
$$Density_{kf} = \frac{\sum_{j \in f, j \neq k} \Phi_{kj}}{\sum_{j \neq k} \Phi_{kj}} \times 100$$

where Φ_{kj} denotes the technological relatedness between technological field k and j . The density takes on values between 0 and 100%, where a larger value indicates that more related technologies belong to the firm's knowledge base. If relatedness does indeed help firms to diversify into new fields we would expect to find a positive relation between this density index and the probability that a firm will enter a new technological field.

Results

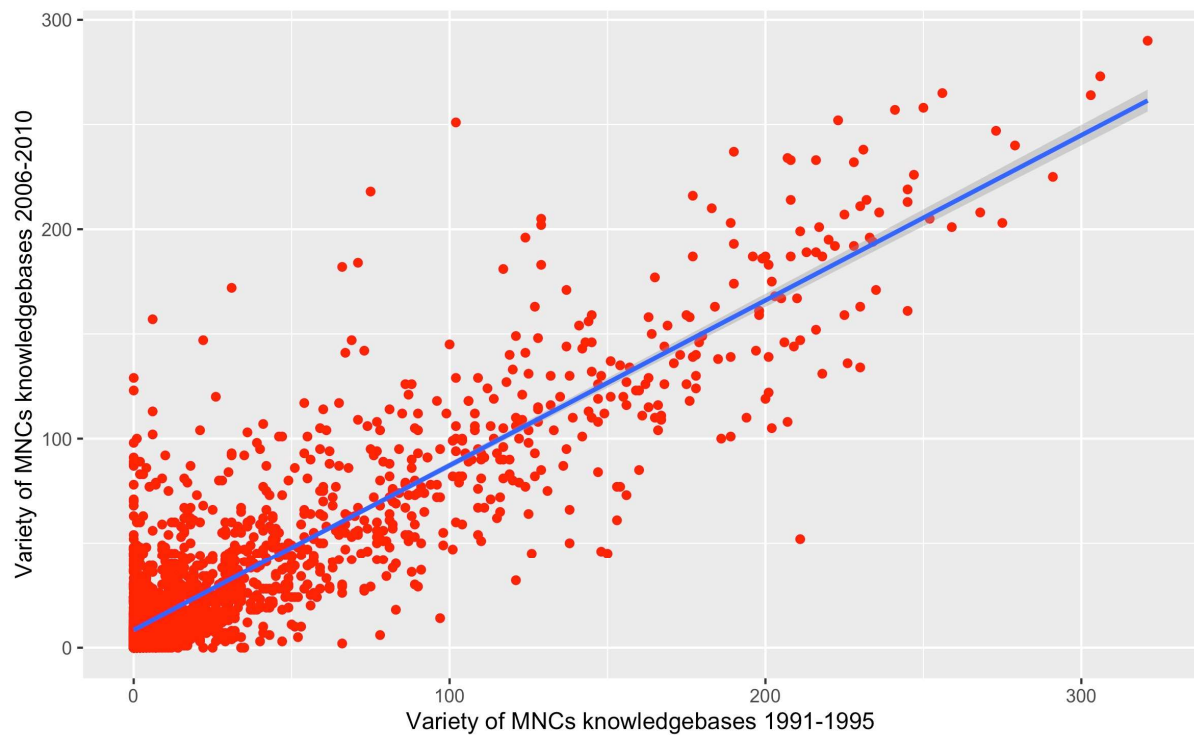
First, Figure 1 provides an illustration of the global map of technology. The map illustrates that some technological fields are more central and more connected than other fields.

Figure 1: Global map of technology

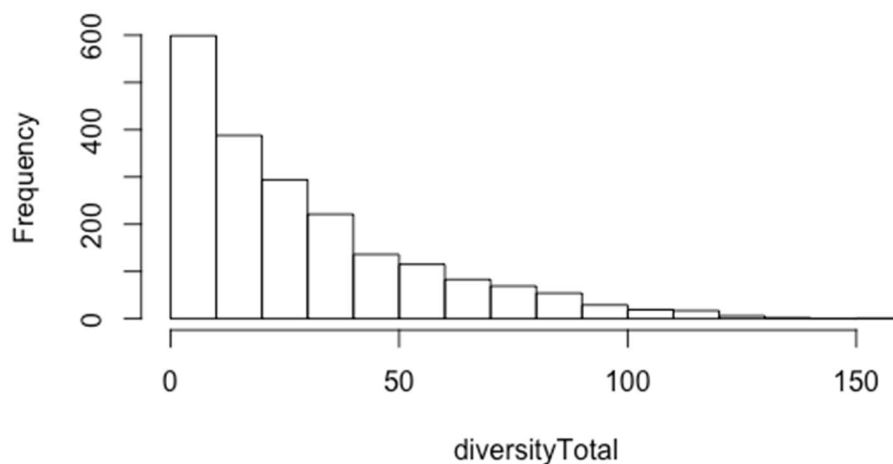


Projecting the technological knowledge bases of individual companies on the map provides insights in how the knowledge bases of firms relate to the global knowledge base at a given time. Figures 2a and 2b illustrate this for a portfolio.

Figure 2 Distribution of diversity of the knowledge base of firms also taking into account balance and distance



Histogram of diversityTotal



Second, concerning the role of technological relatedness in the diversification strategies of firms, Figure 3 suggests a relationship between the relatedness density at firm level and the entry of new technological fields.

Figure 3. Relatedness and technological change in CIB corporations. The rate of entry is the number of new technological fields that entered an MNCs knowledge base divided by the total number of possible entries. Average density is the average percentage of related technological fields for the MNC. Correlation between density and entry is 0.84 (Pearson's product-moment correlation) and significant.



Discussion and conclusion

This study addresses the evolving technological capabilities of all large multinational firms in order to understand patterns of increasing complexity of the knowledge base of firms. The results provide new insights about the mechanisms underlying the global productivity slowdown and patterns of technology divergence. In general, the entry of technologies of firms can be explained by their relatedness to the existing technological portfolio. Related technologies are more likely to enter the portfolio of a firm than unrelated technologies. We find indications that technological progress of the global knowledge base is slowing as indicated by a relative increase in incremental recombinant innovation. Furthermore, we observe that the knowledge base of firms is characterised by increasing complexity and diversity. However, differences among firms and sectors are pronounced. New public policy lessons can be articulated.

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