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Substitutability and complementarity of technological knowledge and the inventive performance of semiconductor companies

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ABSTRACT

This paper analyses whether complementarity and substitutability of knowledge elements are key determinants of the firm's inventive performance, in addition to the more conventional measures of knowledge stock and diversity. Using patent data from 1968 to 2002 in the semiconductor industry, we find that the overall level of complementarity between knowledge components positively contributes to firms' inventive capability, whereas the overall level of substitutability between knowledge components generally has the opposite effect. Yet a relatively high level of substitutability is found to be beneficial for explorative inventions. These results suggest that a firm's inventive capacity significantly depends on its ability to align its inventive strategies and knowledge base structure.

1. Introduction

Several authors have argued that a possible source of heterogeneity in firm performance relates to differences in firms' ability to produce new knowledge (Nelson, 1991; Henderson, 1994; Henderson and Cockburn, 1994; D'Este Cukierman, 2005). In addition to a firm's R&D efforts and accumulated knowledge stock (Mansfield, 1980; Link, 1981; Griliches, 1986; Jaffe, 1986), recent findings have emphasized technological-knowledge diversity as a potent source of a firm's inventive performance (Henderson and Cockburn, 1996; Nesta and Saviotti, 2005; Garcia-Vega, 2006; Quintana-García and Benavides-Velasco, 2008). However, in contrast to what one would expect, accumulating diverse technological knowledge does not lead to technological heterogeneity among firms. Technological (Patel and Pavitt, 1997) and scientific (D'Este Cukierman, 2005) profiles are both stable over time and somewhat similar among firms competing in the same industry.

This paper examines the relational properties of knowledge elements to describe the structure of a firm's knowledge base as a determinant of the firm's inventive performance. We follow early work by Galunic and Rodan (1998), who associate the ability to combine or recombine knowledge elements with the underlying characteristics of knowledge elements. However, we depart from their framework with regard to the nature of knowledge (i.e., tacitness, dispersion, and context specificity) and based on our explanation on the relational properties of knowledge. More precisely, we (1) consider the degree of complementarity and substitutability of knowledge elements as two relational properties of knowledge that characterize the structural composition of a knowledge base and (2) examine whether and the extent to which such dimensions are conducive to economically valuable inventions.

Further, we investigate whether the capacity of a company to successfully engage in exploratory experiments is related to these two knowledge base properties. This question is related to March's (1991) distinction between exploitation (the selection and refinement of existing technologies) and exploration (the invention of new technologies). To produce more and useful knowledge, firms may allocate resources on projects by reusing and deepening existing knowledge or by broadening the scope of their capability portfolio (Katila and Ahuja, 2002). We suggest that this decision does not reflect a simple investment choice problem. The structure of the knowledge base generates specific constraints

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on knowledge accumulation processes, which may condition and affect the probability distribution of the return on each type of project.

The rest of the paper is structured as follows. Building on prior work on knowledge combination, the following section discusses the relationship between a firm's knowledge base structure and its inventive performance. Section 2 presents the analytical framework, and the data set is described in Section 3. Section 4 presents the results from longitudinal studies on a sample of semiconductor companies, and Section 5 discusses the findings and suggests future areas of investigation.

2. Knowledge base structure and inventive performance

2.1. Characterizing the structure of a knowledge base

Characterizing a knowledge base as a collection of links between knowledge elements provides an interesting perspective on a firm's specific capabilities. Knowledge bases have typically been conceptualized as sets of capabilities, information, and knowledge elements on which companies draw for inventive activities and problem solving (Nelson and Winter, 1982; Winter, 1984; Dosi, 1988; Fleming, 2001). Prior studies have considered the knowledge stock accumulated in the knowledge base (Mansfield, 1980; Link, 1981; Griliches, 1986; Jaffe, 1986) and the diversity of knowledge elements (Henderson and Cockburn, 1996; Garcia-Vega, 2006) to be the main sources of differences between firms undertaking inventive activities.

However, the links between technological-knowledge elements may be more important than their diversity. Although firms are increasingly technologically diverse, firms competing in the same industry tend to exhibit similar profiles (Patel and Pavitt, 1997; Granstrand et al., 1997; Gambardella and Torrisi, 1998). Thus, in addition to the capacity to accumulate knowledge, relations between the elements of the knowledge base may reflect idiosyncratic methods of using and exploiting knowledge (Nesta and Dibiaggio, 2003; D'Este Cukierman, 2005). A series of studies have examined the relations between separate elements of a knowledge base to characterize the pattern and evolution of a firm's specific competencies. For instance, the emergence of nanotechnology from combining biotechnology and microelectronics can be traced back to the convergence of physics, engineering, molecular biology, and chemistry competencies that were increasingly integrated into the knowledge base of early entrants developing industrial applications of nanotechnology (Avenel et al., 2007). Likewise, Nesta and Dibiaggio (2003) find a similar homogenization process in the knowledge bases of biotech companies (particularly between firms that specialize in specific industries, such as the agro-food, chemistry, or pharmaceutical industries). Nonetheless, they show that the increasing differentiation in firms' knowledge base structure parallels this convergence of knowledge elements; thus, firms with similar knowledge elements tend to differentiate themselves by developing and exploiting different types of links between knowledge elements.

However, depending on the perceived nature of the links between knowledge elements, a knowledge base structure can have different meanings. According to Henderson and Clark (1990), product development requires both knowledge elements (component knowledge) and architectural knowledge ("knowledge about the ways in which the components are integrated or linked together into a coherent whole") (Henderson and Clark, 1990, p. 11). This concept has subsequently been extended to architectural competence to integrate organizational capabilities that structure problem-solving activities and that facilitate the development of new competencies (Henderson and Cockburn, 1994).

The literature on the structure of the relations between knowledge elements in problem-solving (or search) processes focuses on the interdependencies between knowledge elements, which determine how elements *should be* combined (e.g., Kauffman et al., 2000). While interdependencies are common to all firms, the elements that are integrated into a firm's knowledge base and the combinations thereof are specific to the firm and reveal idiosyncratic beliefs regarding perceived interdependencies (Yayavaram and Ahuja, 2008).

Breschi et al. (2003) consider other types of relations. Relying on the notion of relatedness, as defined in the product diversification literature (e.g., Teece et al., 1994), elements can be related if they were produced through the use of the same underlying type of knowledge. Just as product diversification is less costly if it is based on the use of common-proprietary resources (Teece, 1982), technological diversification may generate economies of scope in research activities if the same knowledge elements are relied on (Henderson and Cockburn, 1996). Furthermore, firms can enjoy learning externalities if they use a given set of problem-solving methods or tools to facilitate the development of different knowledge elements or combinations.

In this paper, we extend this view and analyze the structure of a knowledge base by delineating complementarity and substitution as two different relational properties of knowledge elements. Two complementary elements are elements whose value or usefulness increases when the elements are combined (Milgrom and Roberts, 1990). As Rosenberg (1982) shows, major inventions rely on the available complementary technologies. For example, the laser was first patented in 1960 and could not be applied to telephone signal transmission until the appropriate fiber-optic cable was developed in 1970. Complementarity is more than the simple combination of knowledge elements; it results from the intensive use of two knowledge elements through a combinatorial search process. Kodama (1995), using the example of mechatronics, explains the length of time required for the search process to establish mechanical, electronic, and material technologies as complementary technologies. The combination of ordinary and electric machinery was investigated in 1971 based on servo-motor innovations in the machine tool industry introduced by Fanuc (a spinoff of Fujitsu) and the development of Teflon coating material by Daikin Co. (Kodama, 1995). Then, new combinations were tested with communications and electronics technology later in the early 1970s, giving rise to mechatronics developed in 1975 when precision instruments were included to yield a stable and reliable solution (Kodama, 1995, p. 212). Unlike interdependent knowledge elements, complementary elements can be – and often are – used separately, and their synergy depends on the context in which they are used for specific application domains.

Substitutability characterizes the extent to which elements share similar properties in their use with other elements and, therefore, the extent to which elements tend to be combined with the same other elements. Hence, two elements are substitutable if they complement the same other elements. In a combinatorial search process, alternative options often compete.[1] Substitutable elements may reflect a transitory redundancy until

[1] For instance, in a parallel search process, as illustrated by the Manhattan project (Nelson, 1959; Lenfle, 2011), several options may be necessary under both uncertainty and time pressure. To develop the atomic bomb on time, three competing programs were launched concurrently: the traditional "gun design," wherein an explosion is used to throw two fission materials against each other and thus to create a chain reaction; "the implosion design," wherein the collapse of a plutonium core after the explosion causes the chain reaction; and the "super design," wherein nuclear fusion, not fission, is relied upon. The two first options resulted in two successful projects, "Little boy," which was dropped on Hiroshima, and "Fat Man," which was later dropped on Nagasaki (Lenfle, 2011, p. 366).