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A MODEL OF INNOVATION AND LEARNING WITH INVOLUNTARY SPILLOVERS AND ABSORPTIVE CAPACITY

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ABSTRACT

The purpose of this paper is to develop a model of innovation and learning that incorporates explicitly the need for a firm to conduct its own R&D in order to realize involuntary spillovers from other firms' R&D activity, and the development of absorptive capacity of research firms over time. The conclusions of the model follow directly from the functional forms that are used to describe the generation and absorption of technological knowledge. The first proposition formally characterizes the steady-state rate of growth of technology for the model. The analysis also shows how some of the key features of two distinct, pure modes of organization of the production of new knowledge, the R&D model and the new localized knowledge model, are implied by our model by simply changing drastically the relative magnitude of two exogenous parameters: the ease of learning and the pace of knowledge advance. The second and last proposition formally characterizes the connections implied by the model between involuntary spillovers and absorptive capacity. Analysis of the long-term interactions between involuntary spillovers of knowledge and absorptive capacity provides the essential insights to understand the elements of a self-sustained process of endogenous growth.

KEYWORDS: Innovation, learning, involuntary spillovers, absorptive capacity, endogenous growth, steady-state growth.

1. Introduction

Research and Development (R&D) may be viewed as serving a dual role: innovation and learning. The role that R&D plays in learning has received little attention in the past. Economists conventionally think of R&D as generating innovation in the form of new products and new production processes. As suggested by Cohen and Levinthal (1989), however, R&D not only generates new knowledge, but also enhances the learning capacity of the firm. That is, R&D investments also provide the firm with an in-house technical capacity that facilitates the assimilation of new technology developed elsewhere. A significant benefit of R&D is its contribution to the knowledge base that constitutes the so-called firm's absorptive capacity.

Cohen and Levinthal (1989) introduce the concept of absorptive capacity of firms, which refers to the ability to learn, assimilate, and use knowledge developed elsewhere through a process that involves substantial investments in research and development. This capacity depends crucially on the learning experience of firms, which in turn may be developed and enhanced by in-house R&D activities. Furthermore, Fisher (2003) states that firms, particularly smaller ones which lack appropriate in-house R&D facilities, have to develop and enhance their absorptive capacity by other means, such as interacting with other firms, and taking advantage of knowledge spillovers.

The purpose of this paper is to develop a model of innovation and learning that incorporates explicitly the need for a firm to conduct its own R&D in order to realize involuntary spillovers from other firms' R&D activity, and the development of absorptive capacity of research firms over time. Firms' absorptive capacity is related to their R&D efforts. Differently from conventional economic analysis, involuntary spillovers are assumed in the model not to rain down upon its beneficiaries like manna from heaven. And, firms' absorptive capacity will tend to develop cumulatively. Capturing technological change and organizational learning in the model is essential to understand the dynamic process of absorptive capacity building in research firms.

The conclusions of the model follow directly from the functional forms that are used to describe the generation and absorption of technological knowledge. The first proposition formally characterizes the steady-state rate of growth of technology for the model. Perhaps the most interesting feature of the balanced growth calculated for the model constructed here is that changes in the exogenously given ratio of the ease of learning to the pace of knowledge advance have effects not only on the level of absorption of external knowledge but also on the rate of growth of internal knowledge.

The analysis also shows how some of the key features of two distinct, pure modes of organization of the production of new knowledge, the R&D model and the new localized knowledge model, are implied by our model by simply changing drastically the relative magnitude of two exogenous parameters. In a limit case that may be relevant for understanding the organization of the generation of knowledge that emerged mainly in the USA after the Second World War, if the exogenously given ratio of learning opportunities to innovating opportunities is too low, the growth that takes place depends heavily upon exogenous advances in scientific and technological knowledge, and endogenous R&D efforts exerted within large research firms. In another limit case, diametrically opposed to the first one, that may be relevant for the analysis of the emergent mode of organization of knowledge production based upon the notion of localized technological knowledge, if the exogenously given ratio of learning opportunities to innovating opportunities is too high, the growth that takes place depends heavily upon technological externalities and interactions among research firms, and the appropriate conditions of access to local knowledge externalities.

Analysis of the long-term interactions between involuntary spillovers of knowledge and absorptive capacity provides the essential insights to understand the elements of a self-sustained process of endogenous growth. We thus complete our description of the model of innovation and learning for better understanding the mutual relationships between involuntary spillovers of knowledge and absorptive capacity, and their consequences in terms of steady-state growth of knowledge. The second and last proposition formally characterizes the connections implied by the model between involuntary spillovers and absorptive capacity.

The rest of the paper is organized as follows. Section 2 sets out our formal model, and Section 3 provides the main analytical results derived from the model. Finally, Section 4 concludes the paper.

2. Theoretical framework

We begin our description of the basic model of innovation and learning, consisting of a dynamic system with a number of simultaneous differential equations and a corresponding set of interacting patterns of change. Our mathematical modeling includes a specification of an individual production function of new technological knowledge, a plausible specification of an individual absorptive capacity differential equation, and an identity between two representations of existing knowledge about the technology. A discussion of information and knowledge flows, intangible capital stocks, and their patterns of interactions in the networks underlying the knowledge-based and new economy can be found in Engelbrecht (2003).

Suppose there are N research firms operating in the innovation system. The production function of new technological knowledge of each individual research firm $i \in N$ is given by the following differential equation (where a dot hereafter stands for time derivative):

$$\dot{A}_i = \delta_{IC} H_i A_{IC}\,, \qquad (1)$$

where δ_{IC} is a productivity parameter of every innovating unit, H_i is the amount of the firm's own R&D efforts, and A_{IC} is the knowledge base of the firm's innovative capacity. Such stock of knowledge is an indicator for the knowledge that promotes innovation in the firm. The knowledge related to innovation takes various forms such as patents, publications, and catalogues where descriptions of new products or production processes can be found, as well as skills and competences. To simplify notation, we ignore subscript i in firm i's innovative capacity amount A_{IC}. And we also assume that $\delta_{IC} > 0$.

The rate of technological innovations is affected by the current stock of knowledge related to innovation. The specific functional form of production of new knowledge adopted here follows closely an analogous function in Romer (1990). In Romer, the analogue of δ_{IC} is a strictly positive parameter, and H_i denotes the amount the human capital employed by an individual researcher i, and is measured in terms of years of forgone participation in the labor market. The single relevant difference is that knowledge about the technology is represented there by the number of patented product designs alone. The research sector uses human capital and the available stock of knowledge to produce new knowledge; specifically, it produces designs for new producer durables. Owners of designs have property rights over their use in the production of new producer durables, but inventors have free access to patent applications and learn knowledge that helps in the design of new products. Furthermore, Suarez-Villa's (2000) innovative capacity indicator represents the stock of patented inventions. These are a repository of new ideas and knowledge that have passed the scrutiny and novelty requirement through the patent review process.

Our model postulates that a firm's capacity to absorb externally generated knowledge depends on its R&D effort and stock of prior knowledge related to learning. We characterize the accumulation of firm i's knowledge related to learning such that,

$$\dot{A}_{AC} = \dot{A}_i + \sum_{\substack{j=1 \\ j \neq i}}^{N} \delta_{AC}^{\delta_i} \delta_{AC}^{\delta_j} \beta (H_i A_{AC})^{\delta_i} (\dot{A}_j)^{1-\delta_i}\,, \qquad (2)$$

where δ_{AC} is a productivity parameter of every learning unit, δ_i is the endogenous control the i-th firm can exert on the spillovers that its R&D activity generates through the choice of an R&D approach, β is the fraction of one firm's new technological knowledge that potentially spills over to all other firms' available knowledge, and A_{AC} is the knowledge base of the firm's absorptive capacity. To save notation, we ignore subscript i in firm i's absorptive capacity amounts $\dot{A}_{AC}$ and A_{AC}. And we also assume that $0 < \delta_{AC} < 1$, $0 \leq \delta_i$, $\delta_j \leq 1$, and $0 \leq \beta \leq 1$.

Absorptive capacity has two important elements, prior knowledge base and intensity of effort. Cohen and Levinthal (1990) argue that the ability to evaluate and utilize outside knowledge is largely a function of the level of accumulated prior related knowledge. Relevant prior knowledge base comprises basic skills and general knowledge, but may also include the most recent scientific and technological knowledge. And, intensity of effort represents the amount of time and energy expended by firm members for learning skills. Intensity of effort is critical because it is insufficient to merely expose an individual or a firm to the relevant prior knowledge in order to develop an effective absorptive capacity. A firm's ability to exploit external knowledge is often generated as a byproduct of its R&D activity; thus, a firm' R&D is assumed to satisfy two functions, generation of new knowledge and contribution to the firm's absorptive capacity. Moreover, differential equation (2) describes the accumulation of absorptive capacity of a firm. Cohen and Levinthal's (1990) discussion of the character of absorptive capacity and its role in assimilating and exploiting knowledge suggests the simple generalization that prior knowledge permits the assimilation and exploration of new knowledge. The basic role of prior knowledge suggests the following feature of absorptive capacity that will affect innovative performance of firms: accumulating absorptive capacity in one period will permit its more effective accumulation in the next. Finally, the dynamic representation in (2) is analogous to the representation in Kamien and Zang (2000) of a firm's effective R&D effort that incorporates absorptive capacity as a control variable but in a static setting; besides including the same technological spillover parameters δ_i, δ_j, and β, they are also homogenous functions of degree one.

Let $\delta_{AC}^{\delta_i}$ denote an absorptive capacity weight. We consider the absorptive capacity weight $\delta_{AC}^{\delta_i}$ in (2) to be a function not only of endogenous control δ_i, but also of a parameter δ_{AC} that is shaped by the exogenous factors that affect the character and ease of learning. We have assumed that $0 < \delta_{AC} < 1$, and $0 \le \delta_i \le 1$ for every firm i, so that $0 < \delta_{AC}^{\delta_i} \le 1$. Thus, we are assuming that increasing δ_{AC} increases the absorptive capacity weight, but increasing δ_i decreases it. The larger the absorptive capacity weight, the larger is the marginal impact of own R&D and prior knowledge on absorptive capacity.

We incorporate two dimensions of the ease of learning in our model: internal control, and external factors. Instead, in Kamien and Zang (2000), the representation of a firm's effective R&D effort that incorporates absorptive capacity as a strategic variable includes absorptive capacity weights that are functions only of endogenous controls δ_i and δ_j, i.e., $(1 - \delta_i)$, and $(1 - \delta_j)$. A firm's effective R&D activity can be interpreted as the sum of its own R&D spending and a fraction of the rival's R&D spending. Hence, the i-th firm's effective R&D effort ultimately becomes a decreasing function of both δ_i and δ_j. And, Cohen and Levinthal (1989) argue that the firm's absorptive capacity is determined by the characteristics of the underlying scientific and technological knowledge that affect the ease of learning from the environment. The relevant characteristics of outside knowledge that make R&D more of less critical to the development of absorptive capacity, although hardly possible to specify every one of them, include the character or complexity of the knowledge to be assimilated, and the degree to which the outside knowledge is targeted to the firm's needs and concerns.

Knowledge transfer may occur through various channels as a result of an interactive process within a given network arrangement. Knowledge diffusion may occur via reverse engineering, patent applications, or labor mobility among firms. Moreover, the extent to which knowledge flows through these different channels depends upon a number of exogenous factors. The exogenously given spillover parameter β represents the limited ability a firm has to curtail the involuntary spillovers from its R&D activity, such as the information disclosed when patents are granted, information disclosed in scientific publications, knowledge provided through reverse engineering, and knowledge provided through migration of employees.

The knowledge identity is also a constitutive part of the model specification

$$A_{IC} = A_{AC} . \tag{3}$$

The ability to exploit external knowledge is a critical component of innovative capabilities. In very general terms, technological innovation involves the solution of problems. Cohen and Levinthal (1990) argue that problem-solving and learning capabilities are quite similar. Learning capabilities develop similarly to problem-solving skills, although exactly what is learned may differ. Learning capability is the capacity to assimilate knowledge, which encompasses a firm's ability to imitate, whereas problem-solving skills represent a capacity to create new knowledge, for innovation. Furthermore, closely related to the concept of absorption capacity, is Suarez-Villa's (2000) concept of innovative capacity, which posits that diffusion occurs through the accumulation of knowledge provided by the stock of patented inventions. This stock of knowledge has a potentially strong link to diffusion within networks. And, somehow related to our knowledge identity (3) is Nelson and Phelps' (1966) assumption that the stock of human capital affects both the rate of technological innovations and the rate of diffusion or adoption of existing innovations. The two main sources of human capital accumulation as an alternative source of sustained economic growth are education and learning by doing (Lucas, 1988).

We go on with our work on describing the model by adding a set of complementary assumptions. Integrating (2) with respect to time t yields

$$A_{AC} = A_i + \sum_{\substack{j=1 \\ j \neq i}}^{N} \int_0^t \delta_{AC}^{\delta_i} \delta_{AC}^{\delta_j} \beta (H_i A_{AC})^{\delta_i} (\dot{A}_j)^{1-\delta_i} \, dt . \tag{4}$$

Knowledge related to learning is incorporated in the firm since the birth of the industry. The amount of A_{AC} at any time t is the total knowledge accumulation related to learning that has occurred since $t = 0$. Bear in mind here that, for any i, $A_i(t) = \int_0^t \dot{A}_i(t) dt$.

Suppose that the N research units existing in the research sector are all identical. The supposition that an R&D strategy is symmetric, both in terms of a firm's R&D effort and its R&D approach to endogenously control the spillovers its R&D activity generates, allows us to make important simplifications in the analysis. Let the identical R&D approach correspond to $\delta = \delta_i$, for every $i \in N$. Given that these research firms are all exactly alike, we have equal time derivatives $\dot{A}_j = \dot{A}_i$, $j \neq i$, all the time, and so we can replace the $\sum$ summation symbol in (4) above by factor $(N - 1)$ to yield

$$A_{AC} = A_i + (N-1) \delta_{AC}^{2\delta} \beta \int_0^t (H_i A_{AC})^{\delta} (\dot{A}_j)^{1-\delta} \, dt . \tag{5}$$

We conjecture that

$$A_{AC} = k A_i , \tag{6}$$

where k is a time-invariant multiplicative factor. This is consistent with steady rates of growth of technology. In a steady state the growth rate of A_i is equal to the growth rate of A_{AC}; that is, these two knowledge magnitudes grow at the same constant rate g. After substituting this A_{AC} expression (6) and the $\dot{A}_i$ expression (1) into equation (5) and rearranging, we get as conjectured

$$k = 1 + (N-1)\frac{\delta_{AC}^2}{\delta_{IC}}\beta \,. \qquad . \qquad (7)$$

After applying result (7) into equation (1), we can divide (1) through by A_i, in order to get the expression of the growth rate of internal knowledge. And so growth rate g is a linear function of the knowledge absorption factor k too. Hence, both exogenous parameters δ_{IC} and δ_{AC} determine through k how critical R&D can be to the development of absorptive capacity. We explore in the following section these two critical determinants of R&D in (7), focusing on the effects of the relative weight of the pace of advance and the ease of learning on the generation of new knowledge. The pace of advance of a scientific and technological field, and the degree to which a field is cumulative affect the importance of R&D to developing absorptive capacity (Cohen and Levinthal, 1989).

We have finished our work on describing the basic model. The next move is to carry out the analysis of the model in the following section. We establish two main results from the basic model and then discuss them.

3. Main results

3.1 The generation of new knowledge: steady-state and modes of organization

The first contribution of this paper is to analyze the generation of innovations when R&D plays a dual role in innovation and learning. The main characterization of the behavior of our dynamic system is reported in the following formal statement. The steady-state rate of growth of technology is obtained by solving simultaneously the set of equations (1)-(3), together with equations (4)-(7).

The rate of growth g is positively correlated with both the size of the research firm, H_i, and the size of the innovation system, N, which is incorporated in the knowledge diffusion factor k. The rate of generation of new knowledge derived from the basic model depends on a number of distinct technological spillover parameters through the absorption and diffusion factor of knowledge. Most interestingly here is that increases in the exogenously given ratio of the ease of learning to the pace of knowledge advance lead to increases not only on the level of absorption and diffusion k but also on the rate of growth of knowledge g.

PROPOSITION 1: Externality flows $(N-1)\dot{A}_j$ of involuntary spillovers, and knowledge base A_{AC} of absorptive capacity all increase at the same constant rate as individual production of new knowledge: $g = \delta_{IC} H_i k$.

It immediately follows from this that the extreme view taken in Romer (1990) of the public-good character of knowledge shows up in our paper as a limit case. Public-good aspects of technological knowledge create global knowledge externalities. That is, technological information spills into the atmosphere and other firms with clear incentives can freely take advantage of it.

For a very low R&D specificity parameter δ and a very high exogenously given knowledge spillover parameter β, the rates of generation of new knowledge in our paper and in Romer (1990) become the same. Following Romer, let H_A denote the total amount of human capital employed in the research sector; in terms of our symmetric representation of research units, $H_A = H_i N$. Hence, for $\delta \to 0^+$ and $\beta \to 1^-$, the growth rate of knowledge in our model becomes $g = \delta_{IC} H_A$, as the corresponding diffusion factor of knowledge increases to $k = N$.

We assume that common R&D specificity decreases a firm's absorptive capacity knowledge base, $\partial A_{AC} / \partial \delta < 0$. The higher the common parameter δ, the more firm-specific and less alike the firms' research approaches become. A firm-specific research approach does not generate knowledge spillovers to other firms and at the same time limits the firm's capacity to absorb spillovers from others. The requirement that the firm's absorptive capacity be decreasing in R&D specificity is therefore consistent with our interpretation of the common parameter δ. And, a sufficient condition is that the diffusion factor k of external knowledge, given in (7), be a decreasing function of δ, which implies in turn that the growth rate g of internal knowledge be a decreasing function of δ. Note that A_{AC} and g are expressed in (6) and Proposition 1, respectively, both as linear functions of k. Therefore, we assume henceforth that $\delta_{AC}^2 < \delta_{IC}$.

Kamien and Zang (2000) incorporate absorptive capacity as a strategic variable in their research joint venture model. Every firm's absorptive capacity is limited by the choice of the firms' R&D approaches. In their approach to endogenizing spillovers, the choice of an R&D approach corresponds to the endogenous control δ_i the i-th firm can exert on the spillovers that its R&D activity generates. It is found in Kamien and Zang that when firms cooperate in the setting of their R&D budgets, they choose identical broad R&D approaches, i.e., $\delta = 0$, regardless of whether or not they cooperate in choosing their R&D approaches. On the other hand, if firms behave non-cooperatively in choosing their R&D budgets, then they choose firm-specific R&D approaches, i.e., $\delta = 1$, unless there is no danger of exogenous spillovers.

Instead, in our model, the strategic use of absorptive capacity on the part of firms' management may not always take place. In two limiting situations of our model, symmetric actions of R&D managers to determine common R&D specificity parameter δ do not fundamentally change firms' capability to learn and assimilate innovations generated elsewhere. That is so, in comparative terms, either because (exogenously) very high technological opportunities make innovations very difficult to be learnt and assimilated, or conversely because new knowledge that has been produced is (inherently) very difficult to be controlled privately. That is, the diffusion factor k of external knowledge barely changes with changes in δ when $\frac{\delta_{AC}^2}{\delta_{IC}} \to 0^+$ or $\frac{\delta_{AC}^2}{\delta_{IC}} \to 1^-$, respectively.

We will consider in turn these two opposing situations. In the first case, generation of new knowledge depends heavily upon technological opportunities that stem from exogenous advances in scientific knowledge, and endogenous R&D activities conducted within research firms. Note on what follows that, given $\frac{\delta_{AC}^2}{\delta_{IC}} \to 0^+$ in factor k, weight δ_{AC}^2 vanishes from the specification of rate g. The rate of growth of technology in this special case is an increasing linear function of the scale of operations of the research firm, as measured by H_i.

COROLLARY 1: In a limit case, for a very high exogenously given innovating opportunities parameter δ_{IC} relatively to the exogenously given learning opportunities parameter δ_{AC} (squared), the growth rate of knowledge becomes $g = \delta_{IC} H_i$, given that the diffusion factor of knowledge reduces to $k = 1$.

Furthermore, the market structure of the research sector is expected to be highly concentrated, consisting of a few large research firms. Under the conditions of Corollary 1, the technology of research exhibits increasing returns in a firm's own R&D effort. Suppose that a research firm commits itself to the level H_i of R&D effort over some period of time. The (absolute) rate at which new inventions are being generated within the discrete interval between T and $T' = T + \Delta t$ is then $\delta_{IC} H_i A_i(T) \int_T^{T'} e^{\delta_{IC} H_i (t-T)} dt$. Clearly, the speed of new inventions depends on H_i in a nonlinear fashion. That is, by doubling H_i over the given time interval, the number of new inventions and designs generated by the firm more than doubles. The introduction of new technology by time T' makes use of cumulated knowledge up to time T as well as previous inventions generated between T and T' as a result of the firm's own R&D activity.

In the second case, generation of new knowledge depends heavily upon technological opportunities in terms of technological externalities and interactions among research firms, and the conditions of access to local knowledge externalities. Note on what follows that, given $\frac{\delta_{AC}^2}{\delta_{IC}} \to 1^-$ in factor k, parameter δ_{IC} can be replaced by δ_{AC}^2 in the specification of rate g. The rate of growth of technology in this other special case is an increasing linear function of the scale of operations of the innovation system, as measured by H_A.

COROLLARY 2: In a limit case, for a very low exogenously given innovating opportunities parameter δ_{IC} relatively to the exogenously given learning opportunities parameter δ_{AC} (squared), the growth rate of knowledge is approximately $g = \delta_{AC}^2 \beta H_A$, as the diffusion factor of knowledge expands approximately to $k = \beta N$.

Furthermore, it is expected the co-localization of research firms within the appropriate technological systems for accessing to external knowledge, such as technological districts and technological clusters able to attract a growing number of research units. Under the conditions of Corollary 2, the relevant advantageous conditions for the accumulation of knowledge become available by location in technological districts and technological clusters that are in a regional, technological, and industrial environment conductive of external knowledge. Suppose that local endowments of a specific region are defined in terms of markets for skilled and experienced personnel, scientific and technological infrastructure, and opportunities for socialization with other complementary participants in the innovation process. The conditions for accessing external knowledge within a few attractive locations worldwide are summed up by a high β. Clearly, firms globally select the appropriate sites for the location of their research and development laboratories within technological districts according to such a local endowments.

The two knowledge generation outcomes stated in Corollaries 1 and 2 of the opposing situations under analysis have a lot in common with key aspects of two main models of generation of technological knowledge, respectively, the once dominant R&D model, and the new dominant model based on the notion of localized technological knowledge. Antonelli (2001) presents the key elements of the R&D model based on the large corporation specializing in conducting internal research and development activities, and the new localized knowledge model based on enhanced interaction between learning agents within innovation networks.

The common key aspects of the generation of technological knowledge are summarized next (see Antonelli, 2001). The following key elements of the R&D model are, to an extent, shared by the knowledge generation outcome of Corollary 1 as well. Firstly, scientific discoveries and general laws, elaborated mainly in universities, are part of the generation of new knowledge. Scientific discoveries and laws are eventually translated into new products within the research laboratories of large corporations. Secondly, internal research and development activities are a part of this mode of knowledge production. R&D activities were mainly centralized in large multi-research laboratories within corporations. Finally, important economies of scale and scope in conducting research activities are also part of the generation of new knowledge. Large size provides corporations the opportunities to take advantage of substantial increasing returns in research.

The following key elements of the new localized knowledge model are apparently shared by the knowledge generation outcome of Corollary 2. Firstly, the recombination of existing knowledge, both internal and external to the firm, is part of the generation of new knowledge. Learning processes and accumulation of tacit knowledge play a major role in the research and development activities, while the scientific and generic content in these activities is relatively small. Secondly, the conditions for accessing external knowledge within local and technological systems are a part of this mode of knowledge production. For instance, technological communication is made difficult by the variety and complexity of details and applications in which new knowledge is embedded. Communication systems in place are therefore important for further advances in the production of new knowledge. Finally, agglomeration of research and development activities within technological districts is also part of the generation of new knowledge. Firms select on a global basis the appropriate sites to locate their research and development laboratories according to local endowments. Industrial evidence confirms that innovative activities in specific industries are localized in a few regions.

3.2 Reciprocal effects between involuntary spillovers and absorptive capacity

The second analytical contribution of this paper relates to the reciprocal effects between involuntary spillovers and absorptive capacity. We complete our descriptive framework for understanding the long-term interactions between involuntary spillovers of knowledge and absorptive capacity and their consequences in terms of endogenous growth of knowledge. A better understanding of this involves combining the previous analysis on the patterns of interaction between knowledge stocks and knowledge flows, with an attempt to conceptualize the mathematical functions of involuntary spillovers and absorptive capacity.

Research firms enhance their absorptive capacities by also taking advantage of involuntary spillovers generated elsewhere in the research sector, and an immediate effect of effective absorptive capacities creation is the increase of involuntary spillovers at the system level.

Foray (2004) argues that involuntary spillovers and absorption enhancement of the new knowledge are both features of competition. Individuals and private firms have incentives to produce new knowledge, but they cannot capture all the benefits from their inventive activity. Competitive markets force private firms to increase and maintain their competitive advantage also through adoption and absorption of the new knowledge originated elsewhere. Because private firms have difficulty in controlling access to new knowledge and develop effective absorptive capacities, competitive markets powerfully generate involuntary spillovers, namely, a knowledge infrastructure that creates private and social gains.

In what follows, we define involuntary spillovers available to a firm by the fraction of new knowledge flows $(N-1)\dot{A}_j$ from other research firms to it. That is, the involuntary spillovers from other research firms to firm *i* are

$$IS_i = \beta(N-1)\dot{A}_j . \quad (8)$$

Clearly, IS_i is increasing in β, for given knowledge flows. The interpretation of involuntary spillovers as a fraction of the other firms' R&D spending is employed in Kamien et al. (1992).

Moreover, drawing an analogy with Kamien and Zang (2000), we define a firm's absorptive capacity by the portion of its effective knowledge stock A_{AC}, given by (4), that it derives from the spillover becoming available from the other firms' R&D activity. That is, the firm *i*'s absorptive capacity is

$$AC_i = \delta_{AC}^{\delta_i} (H_i A_{AC})^{\delta_i} . \quad (9)$$

It is required that AC_i be a decreasing function of R&D specificity δ_i, for a given knowledge stock. And so there is a second sufficient condition to be imposed also on δ_{AC} in this model: $\delta_{AC} < (H_i A_{AC})^{-1}$.

The following result states firstly that there is a reciprocal effect between IS_i and AC_i over time involving individual production of new knowledge by research units. Moreover it is stated that IS_i and AC_i have a reciprocal impact on each other in response to changes in technological parameters δ and β.

PROPOSITION 2: Involuntary Spillovers IS_i and Absorptive Capacity AC_i have a mutual effect upon each other. That is to say,

(1) Sequential increases in IS_i and AC_i lead to increases in absolute rates of individual production of new knowledge over time, and vice versa.

(2) IS_i and then AC_i increase with the knowledge spillover parameter β. And, AC_i and then IS_i decrease with the (common) R&D specificity parameter δ.

Our model involves a number of research units whose knowledge outputs produce dynamic repercussions on the other research units through knowledge flows in IS_i and then knowledge stocks in AC_i. In turn, such updated knowledge stocks become fundamental inputs in the research units' production functions of new knowledge. Thus our model constitutes a dynamic system with several simultaneous differential equations and a given set of interacting patterns of change.

Note that it could be depicted in our model a one-period time lag in either diffusion of knowledge from other research units or assimilation of knowledge within each research unit, so that the amount of new knowledge produced in period *t* would determine not current IS_i or current AC_i but either IS_i or AC_i of period $(t + 1)$.

4. Concluding remarks

We have proposed a dynamic model of innovation and learning that incorporates explicitly the need for a firm to engage in R&D itself in order to realize involuntary spillovers from other firms' R&D activity. Our viewpoint is that it is often analytically desirable to avoid detail and go as directly as possible to a summary description of a pure mode of organization of knowledge production.

Our analysis suggests that the exogenous ease of learning and the exogenous pace of knowledge advance are two factors that affect in a decisive manner the growth rate of technological knowledge. Recognition of the dual role of R&D offers important implications for the economic analysis of the generation of technological knowledge. We hypothesized that the R&D model and the new localized knowledge model, two pure dominant modes of generation of new knowledge, are two polar cases. We viewed these pure cases as tying down the two ends of the spectrum of exogenously given ratios of the ease of learning to the pace of knowledge advance along which all real world cases of organization of the production of knowledge must lie.

In addition, we formally characterized the reciprocal relationships between involuntary spillovers of knowledge and absorptive capacity. We conjectured that such connections are likely to take place with strong self-reinforcing effects which can account for steady-state growth of knowledge.

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