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A Technology Acquisition Model: the role of learning and innovation

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Abstract

This paper theoretically analyses the dynamics of knowledge accumulation with the aim of understanding how developing economies can effectively engage in the process of knowledge accumulation. The main focus is on the complementarity between competence building and innovation. Our analysis is based on a simple standard economics model for the sake of clarity in understanding the link between the need for collaboration and competition in the innovation process at the national level. We find that the importance of developing an absorptive capacity in the knowledge generation process cannot be over-emphasized.

Keywords: absorptive capacity, competences, domestic innovation, developing countries
JEL: O11, O30, O40

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I. Introduction

Our analysis of the innovation process is anchored in the evolutionary technological change framework insofar as it has challenged the two fundamental assumptions of the neoclassical growth theory.[2] The process of innovation does not follow a well defined "innovation possibility frontier" along which investors can move costlessly and effortlessly in search of profit maximisation. Knowledge, particularly technological knowledge is very costly and difficult to obtain because of its tacit nature. In other words, investors do not maximise a well-defined objective function. In addition, market asymmetries play a major role in the innovation process and clearly identifiable signals for innovation do not exist in the unstable environment that characterises the innovation process. Hence, while R&D is an important means of accumulating technical and technological knowledge, the "black box" approach is not entirely convincing owing to the strong risk component introduced by uncertainty, and which must be given due consideration.

Evolutionary economics is well suited to our analysis, which consists in gaining insight on why countries differ i.e. shedding some light on the dynamics of economies. The neoclassical growth theory addresses questions of static equilibrium or movements along a "stable" path. It is noteworthy that econometric analyses tend, on the whole, to concur with predictions of evolutionary economics while large gaps are observed between reality and predictions of the neoclassical growth theory.

The fundamental assumption of the evolutionary growth theory, that innovation is oriented by problems emanating from an existing set of economic situations and therefore results from *routine activities*, is crucial for our analysis in that *routine activities* create a milieu for

[2] Pioneered and elaborated by Nelson & Winter (1982), Rosenberg (1986), Freeman (1987) among others, the evolutionary approach emphasises that the innovation process is a process of interactive learning in which actors improve their competences

interactive learning, a corner stone for innovation. Decision makers in innovation depend on experience, which is highly tacit knowledge, rather than on marginal analysis that consists in equating marginal revenue to marginal cost as in the neoclassical theory.

It is noteworthy that the high pace of change in the current economic environment favours tacit elements, which take on a more important role as experience based knowledge becomes increasingly essential in taking accurate decisions that enable firms to remain competitive. Moreover, the structure of the economic environment plays an important role in determining the experiences or competences and capabilities that entrepreneurs are able to accumulate and use. The underpinning idea with regard to competition is that it is mainly provoked by changes in the external environment rather than an internal desire to maximise profits.

Our view is that the notion of competitivity in the innovation process underlies two elements: individual (rational) behaviour accompanied by a suitable dose of interactive or collaborative behaviour among economic agents owing to the importance of learning or acquisition of tacit knowledge in the innovation process. It appears more realistic to consider that a combination of both individual and interactive behaviour leads to a form of *bounded rationality* rather than full rationality as depicted by mainstream economics.

The understanding of these apparently "conflicting" interests (individual versus collaborative behaviour) of decision makers in the innovation process requires simple tools of analysis that will enable us to obtain clear insights and intuitions on the innovation process. A major shortcoming of evolutionary growth modelling, however, is that it does not provide us with tools that make it possible to clearly discern factors that promote or hinder technological progress. It is for this reason that we shall base our analysis of knowledge generation on a standard economics model. First, however, we highlight the stylised facts of the innovation process.

Stylised facts of the innovation process

Economic literature has established stylised facts with regard to the innovation process, which include the following:

- Uncertainty is an integral part of the innovation process. Creation of new knowledge has an inherent component of unpredictability, which creates pressure on the innovation process because of the irreducible risk that is implied. Uncertainty makes knowledge exploitation complex and is to a large extent responsible for asymmetries that are a major feature in the innovation process and that create a selection mechanism.
- The innovation process leads to the creation of new competences, the component that is thought to be responsible for long-run growth, through a process of interactive learning. Learning or production of technological knowledge lies at the core of innovation.
- Knowledge generation depends on a cumulative process that links knowledge exploitation to prior knowledge in the economy. Prior knowledge acts as a basis for the creation of new knowledge that is often incremental in nature.
- Path dependence is a major element of the innovation process because historical characteristics influence the ease and speed with which innovation capabilities of an economy develop. Innovation activities depend on the structural, institutional and social factors that are embedded in historically evolved technical and cultural structures.

- There is an increasingly tight relationship between scientific discovery and innovation: scientific progress is exploited to produce technological knowledge and technical innovation. This tight relationship is witnessed by the increased engagement in R&D activities, investment in the creation of scientists and engineers etc.
- A weak relationship between market demand and innovation output. Although demand influences the market size of particular technologies, it is not dominant in motivating innovative activity; successful innovation requires both demand and supply incentives. Technological opportunities play a major role in driving innovation output since new techniques must be feasible in terms of exploitation. Moreover, new techniques have been found to induce market demand even in cases where income distribution has remained unchanged.

Bearing these facts in mind, the paper analyses the complementary roles of competence building and domestic innovation based on the model developed by Cohen & Levinthal (1989). Section two defines the model at the aggregate level, while section three analyses the process of knowledge accumulation and formalises the absorptive capacity. The complementarity between competence building and domestic innovation are examined in section four. Section five considers diffusion as an innovation process while section six concludes.

II. Modelling knowledge flows

Following Cohen & Levinthal (1989) we assume that a firm's research and development (R&D) not only generates new knowledge, but also improves the firm's ability to identify, assimilate and exploit knowledge spillovers.

In their basic assumption, Cohen & Levinthal (1989) introduce the idea that the ability to assimilate external knowledge is developed through investment in R&D: they suggest that the firm's incentives to invest in R&D in order to improve the absorptive capacity is driven, on the one hand, by the existence of a large quantity of external knowledge to be assimilated and, on the other hand, by an environment in which learning is difficult. Contrary to the standard view, spillovers act as an incentive to invest in R&D for the improvement of the absorptive capacity. Firms' additional knowledge is characterised as follows:

$$z_i = m_i + \gamma_i \left(\theta \sum_{i \neq j} m_j + T \right) \qquad \textbf{1}$$

$$0 \leq \theta \leq 1 \quad and \quad 0 \leq \gamma_i \leq 1$$

Additions to a firm's stock of knowledge are represented by z_i, which is assumed to increase the firms gross earnings, but at a decreasing rate.[3] m_i is the firm's R&D expenditure while m_j is the R&D investments of other firms; γ_i represents the firm's absorptive capacity i.e. the fraction of external knowledge that the firm is able to assimilate and exploit; θ is the extent to which research efforts of firms spillover into the public domain i.e. intra-industry spillovers; T is the quantity of extra-industry knowledge (knowledge from government and university laboratories and knowledge provided by equipment suppliers), and represents technological opportunity in a general manner.

[3] It is assumed that z_i (additions to the firm's stock of knowledge) increases the firm's gross earnings, Π^i where the profit from the additional stock of knowledge is strictly positive i.e. $\Pi^i_{z_i} > 0$.

The underlying assumption of the equation *1* is that the interaction between γ and θ determines the firm's ability to absorb external knowledge: if there are no knowledge spillovers $(\theta = 0)$ there is nothing to assimilate from the environment, while the firm must engage in its own R&D (m_i) in order to build up an absorptive capacity (γ_i) that permits it to assimilate intra-industry and extra-industry knowledge spillovers. Hence, $\gamma_i = 0$ reflects a firm's inability to access existing spillovers.

Cohen & Levinthal assume that the absorptive capacity of a firm increases with its R&D efforts, but at a decreasing rate. Hence, the absorptive capacity of a firm is built up in a cumulative manner although their static model does not capture this point. In addition, the absorptive capacity is affected by other factors represented by the parameter β . These factors influencing the ability to assimilate external knowledge make R&D more or less critical. A large β implies that m_i is critical for γ_i build up: the marginal effect of m_i on γ_i is large when β is large, thus, small amounts of m_i have large effects on γ_i and vice versa.

$$\gamma_i = \gamma[m_i, \beta] \qquad with \quad 0 \le \beta \le 1 \qquad \mathbf{2}$$

$$\frac{\partial \gamma_i}{\partial m_i} \rangle 0 \qquad \frac{\partial^2 \gamma_i}{\partial m_i^2} \langle 0 \qquad and \qquad \frac{\partial m_i}{\partial \beta} \langle 0 \qquad \mathbf{3}$$

$$d\gamma_i = \frac{\partial \gamma_i}{\partial m_i} dm_i \qquad dm_i = \frac{\partial m_i}{\partial \beta} d\beta$$

$$d\gamma_i = \frac{\partial \gamma_i}{\partial m_i} \frac{\partial m_i}{\partial \beta} d\beta$$

$$\frac{\partial \gamma_i}{\partial \beta} < 0 \quad \sin ce \quad \frac{\partial \gamma_i}{\partial m_i} > 0 \quad but \quad \frac{\partial m_i}{\partial \beta} < 0 \qquad \textbf{4}$$

The definition of the parameter β is such that a higher level indicates that a firm's ability to assimilate external knowledge is more dependent on the firm's own R&D activities (m_i). Put differently, a higher β implies a lower γ_i, however, there will be a higher marginal effect of m_i on γ_i. In addition, as external knowledge becomes more complex (for example when other firms' knowledge becomes increasingly tacit and $\theta \to 0$), and which is the case as $\gamma_i \to 1$ the firm will assimilate less of it for a given level of m_i.

An aggregate and dynamic formulation of firms' flow of knowledge is proposed by Criscuolo & Narula (2001) based on the model by Cohen & Levinthal (1989). In their definition of aggregate flow of knowledge, Criscuolo & Narula (2001) attempt to capture factors that are outside the firm and that contribute to the national level of knowledge. These include agglomeration effects, technical orientation of an education system, incentives that induce firms to exploit external knowledge and the public institutional system.

The basic equation by Cohen & Levinthal (1989) is first rewritten to capture knowledge produced abroad that includes external domestic and foreign knowledge. They then propose a dynamic equation of a firm's knowledge flow. For the purpose of our analysis we borrow from Criscuolo & Narula's idea of external domestic and foreign knowledge, but maintain the static definition of Cohen & Levinthal (1989):

$$z_i = m_i + \gamma^d \theta^d \sum_{i \neq j} m_j + \gamma^f \theta^f \sum_k m_k + \gamma^{\mp} T \qquad \textbf{5}$$

$$with \quad \theta^d > \theta^f \quad and \quad \gamma^d > \gamma^f > \gamma^{\mp}$$

R&D investment by firms in the same industry, but located abroad, is represented by m_k while T takes account of both national and international extra-industry spillovers. It is assumed that external domestic knowledge spillovers θ^d have a diffusion intensity that is higher than that of external foreign knowledge spillovers θ^f. It is also assumed that the absorptive capacity for external domestic intra-industry spillovers γ^d is higher than that for external foreign intra-industry spillovers γ^f. Absorptive capacities of intra-industry spillovers are both larger than that for extra-industry spillovers $\gamma^{\mp}$.

At the aggregate level Criscuolo & Narula (2001) assume a single-sector economy in which there are n identical domestic firms in a country, and p identical foreign firms located abroad. To the extent that the absorptive capacities of firms vary across time depending on the amount of R&D effort and that a common knowledge base exists to some degree, the following aggregate equation of knowledge flow at a country level is derived:

$$\sum_{i=1}^{n} z_{it} = \sum_{i=1}^{n} \left(m_{it} + \gamma_{it}^d \theta^d \sum_{i \neq j} m_{jt} + \gamma_{it}^f \theta^f \sum_{k}^{p} m_{kt} + \gamma_{it}^{\mp} T_t \right) \qquad \textbf{6}$$

$$with \quad 0 \leq \gamma_{it}^d \leq 1; \quad 0 \leq \gamma_{it}^f \leq 1 \quad and \quad 0 \leq \gamma_{it}^{\mp} \leq 1$$

The above formulation in *6* represents a variety of equations that lie between two extremes. In one extreme case, it is assumed that firms have exactly the same knowledge base (there are no domestic intra-industry spillovers), and assimilate exactly the same international and extra-industry knowledge spillovers. In the alternative case, each firm has a completely different knowledge base and, hence, different R&D efforts that determine the extent of spillovers. Here, intra-industry spillovers are relevant and the firms' capacities to absorb external knowledge differ. At the aggregate level the two alternative cases are represented by equations *7* and *8* respectively.

$$Z_t = M_t^d + \theta^f M_t^f \sum_{i=1}^{n} \gamma_{it}^f + T_t \sum_{i=1}^{n} \gamma_{it}^{\mp} \qquad \mathbf{7}$$

$$Z_t = M_t^d + \theta^d (n-1) m_t \sum_{i=1}^{n} \gamma_{it}^d + \theta^f M_t^f \sum_{i=1}^{n} \gamma_{it}^f + T_t \sum_{i=1}^{n} \gamma_{it}^{\mp} \qquad \mathbf{8}$$

$$where \qquad Z = nz; \quad M^d = nm; \quad M^f = pm$$

Following Criscuolo & Narula (2001), we maintain the assumption that firms have the same knowledge base for the sake of simplicity.

$$let \qquad \gamma_t^f = \sum_{i=1}^{n} \gamma_{it}^f$$

$$and \qquad \gamma_t^{\mp} = \sum_{i=1}^{n} \gamma_{it}^{\mp}$$

We maintain equation *7* and re-write it as:

$$Z_t = M_t^d + \gamma_t^f \theta^f M_t^f + \gamma_t^T T_t \qquad \textbf{9}$$

We assume that a country's absorptive capacity is $\gamma_t = \gamma_t^f + \gamma_t^T$, and that θ^f is constant indicating that the degree to which foreign knowledge spills over does not vary - changes in *potential* spillovers result only from variations in foreign innovation efforts. However, not all the *potential* spillovers are accessible for assimilation by the domestic firms. Accessible spillovers may be referred to as *actual* spillovers and depend on the absorptive capacity. At a high level of technology, domestic firms will have absorbed most of the knowledge spillovers and will, therefore, have a reduced backlog: the smaller the backlog of *potential* spillover the more tacit the knowledge. Hence, despite an improving absorptive capacity the possibility of assimilating the remaining backlog will be increasingly weak up to a point where spillovers will no longer exist.

III. Analysis of knowledge accumulation

Following Cohen & Levinthal (1989), it is assumed that a parameter β representing characteristics of the environment affects the development of an absorptive capacity by influencing the marginal effect of R&D on the absorptive capacity. We attach a slightly different meaning to β based on the Cohen & Levinthal (1990) notion that there are two factors affecting an economic agent's incentive to invest in the absorptive capacity via innovation, namely: the difficulty of learning and the quantity of knowledge to be assimilated.[4] It is important to note that in addition to interpreting the characteristic of the environment differently from Cohen & Levinthal (1989), we regard innovation investment in the broad sense rather than merely R&D expenditure. Innovation appears more appropriate

[4] Criscuolo & Narula (2001) interpret β as the gap from the technological frontier.

insofar as *routine activities* contribute greatly to the innovation process, and owing to the fact that we are primarily concerned with knowledge generation in developing countries that do not engage in R&D activities, but may nonetheless generate incremental knowledge.

We propose, therefore, that one of the characteristic of the environment represented by β that affects the absorptive capacity of firms is related to the “systems of innovation”, institutions as well as the networks and linkages among all agents in economy including firms, organisations, government agencies, consumers, etc that have roles to play in the adoption and diffusion of knowledge. More generally, we assume that this characteristic refers to the local knowledge that includes knowledge generated locally, networks of trust and association, etc. Local knowledge plays an important role in influencing the overall technical efficiency of an economy and the ability to identify, evaluate and assimilate foreign knowledge by fostering competence building and upgrading. It eases learning through *inter alia*, reducing vulnerability and improving knowledge flows, consequently strengthening local initiative and collaboration. We assume that local knowledge is reflected by the *learning capability* and is represented by δ, a factor that plays a key role in developing an absorptive capacity and generating as well as diffusing knowledge. A large δ implies a high level of local knowledge and, hence, an increased capacity to improve *knowledge overlap or congruency* with external knowledge that consequently facilitates take-off of a follower country.

We assume that the learning capability (δ) influences the marginal effect of innovation investment thereby affecting the absorptive capacity. A large δ (less obstacles to knowledge adoption due to increased knowledge overlap) reflects the ability of the country’s learning capability to support assimilation of external technology, i.e. a larger absorptive capacity γ_t, but a lower marginal effect of innovation investment on the absorptive capacity.

In other words, for a given amount of innovation investment as $\delta \to 1$ it becomes increasingly difficult to increase γ_t : although the marginal effect of innovation investment is boosted by the growth of the learning capability δ, as $\gamma_t \to 1$ the effect of δ on the absorptive capacity becomes increasing small because of the falling amount of knowledge available for assimilation or the increasing difficulty of accessing it.

We suggest that another characteristic of the environment represented by β reflects the *complexity or tacitness* of knowledge (μ) and is closely related to δ as we shall see shortly. The marginal effect of innovation investment on the absorptive capacity decreases as μ increases: as μ increases, there is a negative effect on the absorptive capacity (γ) . In addition, when μ is very high the amount of *potential* knowledge spillovers is approximately equal to zero regardless of the high absorptive capacity $(\gamma \equiv 1)$. Put differently, higher technology sophistication as $\mu \to 1$ implies that the amount of *potential* spillovers falls (where it is assumed that θ the extent to which research efforts of firms spillover into the public domain does not vary).

The two characteristics δ and μ are closely related in that they constantly act as opposing forces on the absorptive capacity so that, while a high δ boosts the absorptive capacity, a high μ slows it down and vice versa. More precisely, at the initial stages of development of the absorptive capacity, when both parameters are low, the effect of δ on innovation investment overrides that of μ so that the innovation investment effect is more critical on the absorptive capacity. However, as both parameters grow with the growth of innovation investment, the effect of μ on innovation investment may not equal or override that of δ as this would nullifying the positive effect of the latter on the absorptive capacity. This may suggest that unless δ increases at a faster rate than μ , the growth of the absorptive capacity may be hindered. However, increases in both δ and μ act as incentives for increase in innovation investment: a growing δ incites innovation investment because of its positive effect on the absorptive capacity, while a growing μ incites innovation investment because of the growing need to overcome the increasing complexity of knowledge. While increased innovation investment consequently enhances both δ and μ , it may be necessary to deploy other means of enhancing δ so that its effect on the absorptive capacity continues to override that of μ . These other means would include improving the education of the workforce - particularly with regard to science and technology related skills - and linkages of knowledge exchange.

In our analysis we consider that as δ and μ grow, the absorptive capacity may continue to grow with increased innovation investment albeit at a decreasing rate: the marginal effect of innovation investment on the absorptive capacity falls owing to the fact that *potential* knowledge spillovers are increasingly low as knowledge becomes increasingly tacit or highly complex. Hence, the size of μ indicates the amount of foreign knowledge available for assimilation and exploitation by the country - it reflects the country's level of technology sophistication (technology level) or in more common terms its distance from the technology frontier.

The parameter β, the distance from the technological frontier, is represented by both δ and μ , such that small values of δ and μ represent a large value of β and, hence, a large distance from the technology frontier or similarly a large amount of spillovers available for assimilation. These factors (δ, μ) reflect the broad concept of what Abramovitz (1994) termed social capability – highly educated workforce, good infrastructure, an efficient financial system, etc. that facilitate assimilation of spillovers. As in Cohen & Levinthal (1990) they influence the ability to assimilate external knowledge making innovation investment more or less critical: their impact on the absorptive capacity necessarily transpires through investment in domestic innovation.

$$\gamma_t = \gamma(M_t, \beta_t) \qquad with \quad 0 \leq \beta_t \leq 1$$

is rewritten as

$$\gamma_t = \gamma[M_t, \delta_t, \mu_t] \qquad with \quad 0 < \delta_t < 1 \quad and \quad 0 < \mu_t < 1 \qquad \textbf{10}$$

$$and \quad \frac{\partial \gamma_t}{\partial M_t} > 0 \qquad \frac{\partial^2 \gamma_t}{\partial M_t^{\ 2}} < 0 \qquad \textbf{11}$$

We assume that the learning capability is strictly greater than zero $(\delta_t > 0)$ because some learning capability, no matter how minimal, will exist since all societies have a form of social capital. The assumption of a learning capability that is strictly less than one $(\delta_t < 1)$ appears realistic because the capacity to learn cannot be saturated. This is in line with the underlying idea that knowledge creation is unbounded.[5]

Similarly, knowledge complexity is strictly greater than zero $(\mu_t > 0)$ because no knowledge is acquired automatically, while at the same time no knowledge in its entirety is inaccessible

[5] Unbounded growth is possible to the extent that the possibility of creating new knowledge in not finite, Romer (1990)

$(\mu_t < 1)$ i.e. no matter how difficult the access of knowledge, there are always possibilities of identifying some leeway.

As explained previously, small values of δ_t and μ_t imply that a country's ability to assimilate external knowledge is more responsive to innovation investment efforts than large ones. In addition, increases in both δ and μ act as incentives for innovation investment, which impacts positively on the absorptive capacity. Therefore, the effects of δ and μ on the absorptive capacity may be seen as occurring through innovation investment: this indirect effect is positive.

$$if \quad \frac{\partial M_t}{\partial \delta_t} > 0 \quad \frac{\partial M_t}{\partial \mu_t} > 0 \quad then \quad \frac{\partial \gamma_t}{\partial \delta_t} > 0 \quad \frac{\partial \gamma_t}{\partial \mu_t} > 0 \qquad \textbf{12}$$

The indirect relationship between the absorptive capacity and these two factors, δ and μ , is demonstrated by the following:

$$\sin ce \quad d\gamma_t = \frac{\partial \gamma_t}{\partial M_t} dM_t \qquad dM_t = \frac{\partial M_t}{\partial \delta_t} d\delta_t + \frac{\partial M_t}{\partial \mu_t} d\mu_t$$

$$d\gamma_t = \frac{\partial \gamma_t}{\partial M_t} \frac{\partial M_t}{\partial \delta_t} d\delta_t + \frac{\partial \gamma_t}{\partial M_t} \frac{\partial M_t}{\partial \mu_t} d\mu_t$$

$$\frac{\partial \gamma_t}{\partial \delta_t} = \frac{\partial \gamma_t}{\partial M_t} \frac{\partial M_t}{\partial \delta_t} > 0 \qquad and \qquad \frac{\partial \gamma_t}{\partial \mu_t} = \frac{\partial \gamma_t}{\partial M_t} \frac{\partial M_t}{\partial \mu_t} > 0$$

a. The role of the absorptive capacity

Cohen & Levinthal (1990) argue that prior knowledge strongly underlies the development of an absorptive capacity; the ability to identify, assimilate and exploit external knowledge is largely a function of prior knowledge, which at the most elementary level includes basic skills. They identify two features of the absorptive capacity. Firstly, possession of prior related expertise permits easier identification, assimilation and exploitation of outside knowledge. Secondly, accumulation of absorptive capacity in one period facilitates more efficient building up of the absorptive capacity in the next period.

Accordingly, for a country to recognize the importance of developing its absorptive capacity it must possess the ability to make such an evaluation. The ability to recognize the importance of developing an absorptive capacity comes from the existence of an absorptive capacity Cohen & Levinthal (1990). This brings to the fore the importance of clearly understanding the factors that create the 'initial' absorptive capacity. As suggested by Cohen & Levinthal (1990) prior knowledge is the foundation of the 'initial' absorptive capacity. It appears then that once a *certain threshold level of prior domestic knowledge* is reached the cumulative and interactive process linking exploitation of foreign knowledge and domestic knowledge, suggested by Cohen & Levinthal (1990), may be triggered off: an absorptive capacity enhances further accumulation of technological knowledge and in turn technological knowledge enhances further development of the absorptive capacity.

The *threshold level of prior domestic knowledge* may be interpreted as an efficient mix of learning capability and the existing domestic knowledge rather than a stock of knowledge *per se*. In other words, the learning capability should be strong enough to support the building up of domestic knowledge, which in turn would support the learning capability, eventually leading to the cumulative and interactive process. This definition goes beyond the stock of R&D, and is also more appropriate particularly for developing countries that barely invest in R&D, but possess some form of domestic knowledge that can be nurtured and developed through innovation investment.

b. Formalisation of the absorptive capacity function

We assume that creation and development of an absorptive capacity that triggers the cumulative and interactive process between foreign and domestic knowledge fundamentally depends on local/domestic knowledge: domestic knowledge as we saw previously largely determines the learning capability. In addition the process is maintained and heightened by development of local knowledge, which responds to economic changes and is therefore not static. We note that economic changes may undermine local knowledge, leading to weakened learning capability, and consequently to weakened knowledge accumulation and development of the absorptive capacity.

We postulate that if local knowledge is developed via innovation, and thereby the learning capability, a country may take-off with a lower *level* of prior domestic technological knowledge and develop its absorptive capacity more rapidly while using its knowledge more efficiently. Both the *learning capability* and *tacitness of knowledge* affect the curvature of the growth of the absorptive capacity, which assumes an S-shaped curve and can therefore be represented by a sigmoid function as follows[6]

[6] The learning capability affects the curvature of the absorptive capacity via its effect on profitability : a high learning capability induces profitability by enhancing the capacity to take advantage of new opportunities, while profitability encourages the build-up of the absorptive capacity via increased innovation. In other words, a high learning capability influences the speed at which the absorptive capacity grows, while the rate of growth of the absorptive capacity is responsible for the speed of technological catch-up. The tacitness of technological knowledge affects the absorptive capacity in the manner described above.

$$\gamma_t = \frac{1}{1 + \exp[-(\delta_t * \mu_t) Z_t]} \qquad \textbf{\textit{13}}$$

The absorptive capacity increases with technological knowledge, $\gamma_t = \gamma(Z_t)$, and the indirect effects of the learning capability (learning capability increases with overlap or congruency of local knowledge base with foreign knowledge base) and the tacitness or complexity of knowledge (as knowledge spillovers approach zero). As the learning capability δ and the tacitness of knowledge μ grow, they induce more innovation investment and the absorptive capacity continues to grow, but finally peters off growing asymptotically as $\gamma \rightarrow 1$. This functional form of the absorptive capacity, pioneered by Mansfield (1961) for a set of sample parameters, initial stock of knowledge as well as domestic and foreign innovation, approximates the stylized S-shaped function of technology diffusion models. This approximation appears realistic given the fact that the absorptive capacity is based on technology assimilation.

This function may be represented as in figure *1* here below.

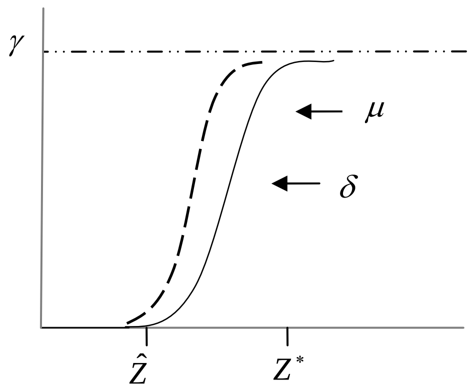

Figure 1: The absorptive capacity curve and the impact of learning capability

IV. Effects of increased learning and innovation

Departing from equation *9*, which represents additions to the aggregate stock of knowledge, we define a non-linear static model for knowledge accumulation (additions to the stock of knowledge) where the non-linearity has a sigmoid form. We drop the term representing extra-industry knowledge for the sake of simplicity, and re-write the equation as:

$$Z_t = M_t^d + \gamma^f(Z_t)\cdot\left(\theta^f M_t^f\right) \qquad \textbf{\textit{14}}$$

This implies that the dynamic equation additions to the aggregate stock of knowledge may be derived as follows:

$$\dot{Z} = \dot{M}^d + \frac{\partial\gamma^f}{\partial Z}\cdot\frac{dZ}{dt}\cdot\theta^f M^f + \gamma^f(Z)\cdot\theta^f\dot{M}^f$$

$$\dot{Z}\left(1-\frac{\partial\gamma^f}{\partial Z}\cdot\theta^f M^f\right) = \dot{M}^d + \gamma^f(Z)\cdot\theta^f\dot{M}^f$$

$$\dot{Z} = \frac{\dot{M}^d + \gamma^f(Z)\cdot\theta^f\dot{M}^f}{\left(1-\frac{\partial\gamma^f}{\partial Z}\cdot\theta^f M^f\right)}$$

The second term of the denominator $\left(\frac{\partial\gamma^f}{\partial Z}\cdot\theta^f M^f\right)$ must equal zero in order for the equation to have a solution.

$$\gamma^f = \frac{1}{1+e^{-\frac{\delta}{\mu}Z}} = \left(1+e^{-\frac{\delta}{\mu}Z}\right)^{-1}$$

$$\frac{\partial \gamma^f}{\partial Z} = -\left(1+e^{-\frac{\delta}{\mu}Z}\right)^{-2} \cdot \left(-\frac{\delta}{\mu}\right)e^{-\frac{\delta}{\mu}Z} = \frac{\delta}{\mu}\left(1+e^{-\frac{\delta}{\mu}Z}\right)^{-2} \cdot e^{-\frac{\delta}{\mu}Z}$$

$$where \quad e^{-\frac{\delta}{\mu}Z}{}_{\to 0}$$

Hence, $\frac{\partial \gamma^f}{\partial Z}{}_{\to 0}$ must approach zero faster than $\dot{M}^f_{\to\infty}$ approaches infinity: the absorptive capacity increases with knowledge accumulation albeit at a decreasing rate while knowledge spillovers grow infinitely. The solution to knowledge growth is given by:

$$\dot{Z} = \underbrace{\dot{M}^d}_{domestic\ R\&D} + \underbrace{\underbrace{\gamma^f(Z)}_{absorptive\ capacity} \cdot \underbrace{\theta^f \dot{M}^f}_{potential\ spillovers}}_{actual\ spillover} \qquad \textbf{\textit{15}}$$

It may be interesting to understand the effect of spillovers as a country accumulates technology. From equation *15* above, we consider that the *potential* spillovers, the maximum spillovers that may be accessed by a country at any time, are determined by both the amount of R&D expenditure of foreign firms in the industry (M^f) and the parameter (θ^f) the degree to which research efforts of foreign firms spill into the public domain and is assumed to be constant. However, p*otential* spillovers increase inifinitely with R&D investment by foreign firms, but at a decreasing rate as the complexity or tacitness of knowledge increases despite expanding efforts of R&D investment. The *potential* spillovers may be represented by a monotonically increasing power function.

The *actual* spillovers $\left(\gamma^f(Z)\cdot\theta^f\dot{M}^f\right)$ increase with the growth of the absorptive capacity $\left(\gamma^f(Z)\right)$, but at a decreasing rate as the *potential* spillovers that are yet to be exploited become increasingly tacit i.e. it is assumed that the least tacit knowledge is acquired first and the acquisition process continues progressively towards increasingly tacit knowledge. This implies that as an economy becomes increasingly sophisticated as it acquires increasingly sophisticated knowledge.

We assume that equation *15* may be represented by an S-shaped curve as shown in figure *2* below.

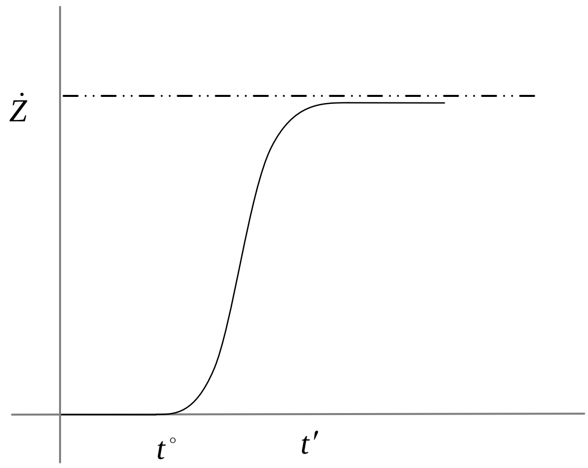

Figure 2: The S-shaped technology accumulation curve

The growth rate of knowledge flow before time t° is constant, that is, the *flow* of knowledge $\dot{Z}$ remains unchanged. When the critical mix of learning capability and domestic knowledge is attained at point t°, the rate of knowledge growth increases (take-off occurs). Between t° and t' the rate of knowledge accumulation increases sharply, but grows at a decreasing rate, as a country exploits the backlog of knowledge, and the interactive and cumulative process between knowledge accumulation and assimilation of foreign knowledge sets in. At time t' the country reaches the frontier point where growth of knowledge flow stagnates due to a diminished amount of knowledge backlog or with the increased tacit nature of knowledge at the frontier.[7]

The three apparent phases of knowledge accumulation merit further discussion. First there is the pre-take-off phase before point t°. It may be the case that knowledge spillovers are *not recognizable* or *not accessible* to the country for assimilation because no absorptive capacity has been developed $(\gamma = 0)$. New ideas embedded in spillovers may be too distant from the country's existing knowledge base to be either appreciated or accessed, Cohen & Levinthal (1990). Hence, before point t°, countries may experience a crabbing situation in which they fall further behind and are unable to reach point t°. Indeed, most developing countries are locked in this growth crabbing situation and continue to face increased marginalisation. The distance to technology frontier is relatively large and may continue to grow. Domestic innovation is therefore crucial for development of the absorptive capacity (the marginal effect of domestic innovation on the absorptive capacity is very high). The importance of studying this crabbing situation cannot be overemphasized, although the bulk of economic literature focuses on - the catching-up phase – the situation beyond point t°. Although beyond the scope of this paper, this lacuna requires attention.

Once a critical mix of learning capability and domestic knowledge has been attained, development of the absorptive capacity begins to take place and the virtuous interactive and cumulative process of technology accumulation and development of the absorptive capacity sets in. This is the catching-up phase and lies between t° and t'. The analysis of spillovers becomes relevant once take-off has occurred and before catch-up. Initially, as the country

[7] If our assumption of non evolving frontier is lifted, new opportunities arise and the knowledge accumulation process continues albeit at a lower rate than between the take-off and the frontier points.

develops its absorptive capacity (γ) more and more spillovers are assimilated and in turn γ grows faster. However, the amount of knowledge spillovers begins to decline as the country's $\gamma \to 1$ and knowledge becomes more complex. Although knowledge spillovers are eventually barely existent, γ continues to grow with the country's expansion of R&D efforts only.

Finally, a country reaches the technology frontier at point t' and there is more reliance on basic research and diversified research since the amount of intra-industry knowledge is smaller and highly tacit, and the country assimilates none of it regardless of increased R&D efforts. Beyond point t' the absorptive capacity becomes irresponsive to a country's R&D effort: the growth of γ quickly peters out as it eventually ceases to be endogenous $(\gamma \equiv 1)$ and growth is entirely propelled by efforts in domestic R&D. If there is concomitant investment by domestic and foreign firms, new technological opportunities will arise and the interactive and cumulative process of growth may proceed from point t': a window of opportunity may occur after point t', and may be represented by a new sigmoid curve that develops to the right of point t°.

Figures *3* and *4* below illustrate the effect of increased learning and innovation investments on the flow of knowledge. They portray the technology accumulation curve described above along with two other single curves.

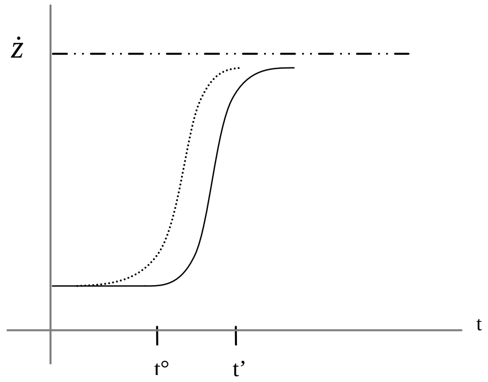

Figure 3: Effect of increased innovation effort on technology accumulation

The continuous single curve in figure *3* depicts the effect of an increased amount of innovation investment on technology accumulation. The upward shift of the technology accumulation curve corresponds to earlier take-off as well as faster technology accumulation process such that the frontier is reached at an earlier date.

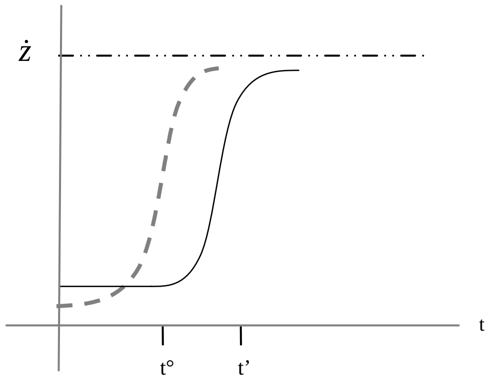

Figure 4: A combined effort of innovation & absorptive capacity on technology accumulation.

The dotted curve in figure *4* shows that the simultaneous development of domestic innovation and the absorptive capacity leads to a feedback support mechanism: a lower critical *level of prior knowledge* may be sufficient for take off and the growth rate to the frontier point may increase. A combined effort of increasing innovation and improving absorptive capacity permits a country to take-off earlier with a *lower level of prior knowledge* and to reach the frontier point at an earlier date as shown in figure *4* below.

In summary, we observe that lack of or inadequate investment in domestic innovation slows the growth of technological knowledge, which is a prerequisite for the development of an absorptive capacity that triggers take-off and maintains the virtuous interactive and cumulative process. In addition, the development of the absorptive capacity (γ) presupposes the existence of sufficient learning capability, which appears to be a central element in driving the catching-up process. Hence, a weak learning capability delays take-off, slows down the catching-up process and may spark off a vicious circle because the domestic knowledge, on which it is built, is prone to erosion as technological changes occur: learning capability therefore requires continuous development and perhaps at an increasing rate that is made possible essentially through domestic innovation.

In figure *2* above, take-off may be delayed beyond point t° by a weak learning capability. In other words, take-off will be delayed until the learning capability attains a level that is sufficient for the build-up of an absorptive capacity. Previously, we argued that a certain *threshold level of prior knowledge,* which we interpreted as an *efficient mix* of learning capability and stock of knowledge, is necessary for take-off. Indeed, a fairly high learning capability may provoke take-off at a relatively lower level of knowledge stock as was the case in Singapore, while a fairly weak learning capability may postpone take-off or thwart it altogether even at a relatively high level of knowledge stock as in the case of some transition economies. This is because the interactive and cumulative process, which underlies successful take-off and the speed at which catching-up takes place, depends on the flexibility of the learning capability.

Verspagen (1991) suggests that for countries that are yet to take off, building-up of the learning capability must take place during the pre-catching-up phase before catching-up can become a relevant process. Moreover, time is continually running out for lagging countries because of the continuous technological changes that are constantly taking place and exerting pressure on economies. It has also been noted that once take-off has occurred it may be the case that the learning capability must develop at an increasing rate so as to fully exploit spillovers and facilitate catch-up, particularly as growth of the absorptive capacity becomes increasing irresponsive to R&D investment, Keller (1996).

If a country fails to develop its absorptive capacity as a result of inadequate investment in both innovation and learning capability in an initial period, whether out of choice or shortage of investment resources, a lock-out situation may result and progressively further marginalise the country as technological transformations continue to take place. In view of our main focus that consists in seeking an understanding of why some developing countries are not only unable to take off, but continue to fall further behind.[8] However, our knowledge diffusion analysis in this paper is assumed to take place along a stable path: this analysis falls short of a realistic explanation of the diffusion process that provides insight into how an economy's structure evolves over time as the innovation process takes place. This is particularly because knowledge diffusion dynamics in an equilibrium analysis is treated as a "once and for all" phenomenon that takes the form of an appendage to the innovation process, whereas it is an integral part of it and is responsible for sparking off a series of minor modifications, which transform the pattern of knowledge transmission and adoption as we shall see in the following section.

[8] This observation is taken into consideration by Wamae W. (2006) "Why technological spillovers elude developing countries: a dynamic non-linear model," *DRUID working paper no. 06-2*

V. Diffusion as an innovation process

Incremental changes, which are part and parcel of the innovation process, play a major role in shaping the knowledge diffusion process. Indeed, innovation and diffusion are two complementary elements in the knowledge production process that operate within a feedback mechanism, and ultimately transform the structure of an economy. The analysis of this feedback mechanism is instrumental in understanding how structural changes take place over time.

The sigmoid curve approach does not take into account the feedback mechanism between the innovation and diffusion processes although it is a major contribution to a 'stylised fact' of the knowledge acquisition process, Dosi (1996). The feedback mechanism is illustrated by Metcalfe (1982) who develops a model that incorporates price changes resulting from innovations and learning effects. Metcalfe illustrates two points: first that different prices are associated with different diffusion curves, and second that a diffusion path represents both movements along a curve as well as shifts of the curve that are provoked by price changes. These two points are centred on the diffusion-innovation nexus in terms of the feedback mechanisms operating between them with regard to both production and demand, and impacting on prices. As stressed by Dosi (1996), on the one hand, market asymmetries push investors to innovate (leading to incremental innovations and improvements) in order to penetrate the market, and, on the other hand, consumer behaviour induces adjustments that are carried out through innovation. *"The diffusion process is usually dependent upon a stream of improvements in the performance characteristics of an innovation, its progressive modification and adaptation to suit the needs or specialized requirements of various submarkets, and upon the availability and introduction of other complementary inputs that make an original invention more useful…"*, Rosenberg (1993).

Competences underlie the successful working of the innovation and diffusion feedback mechanisms. In particular, local technological knowledge is crucial in providing incremental modifications and adaptations that match the needs of the local environment. Economic literature provides a vast literature on evidence of local competence contribution to technological growth, especially in terms of labour mobility which creates large learning effects because the tacit nature of knowledge requires interaction for effective transmission. In passing, we note that the importance of competences in technological change largely accounts for the generally slow pace of knowledge diffusion owing to their tacit nature, as well as differences in environment conditions and, hence, the importance of knowledge localisation.

In view of the dynamic feedback mechanism that underpins knowledge *diffusion as an innovation process*, emphasis on the catch-up process, as often presented in standard economics, while useful in terms of simplicity and clarity, is perhaps not relevant *per se* for policy implication in developing countries. This observation is based on two elements. Firstly, developing countries face a set of widely different economic problems in comparison to that of industrialised countries, which are either at the technology frontier or have a substantial capacity to attain the frontier. Most developing countries are struggling with the question of take-off, and that of catch-up cannot be raised quite yet, if at all. Moreover, since technology acquisition is highly dependent on environmental conditions (local economic problems are highly country specific and current international conditions on technology acquisition are rife with constraints compared to past periods) the technology acquisition process of industrialised countries may not provide clear insight. Secondly, the technology frontier is a moving target based on a cumulative process of knowledge acquisition that is highly path dependent. The implication here is that it would be somewhat illusionary for a developing country with a non existent innovation system and absorptive capacity to envisage catch-up with industrialised countries. In addition, since diffusion curves differ with prices and shift with price changes provoked by incremental changes in the innovation process, the assumption that knowledge diffusion patterns take the form of a logistic curve is rather strong.

VI. Conclusion

In this paper, we have seen that in developing countries where competence enhancement may be stagnant or slow, investment in incremental changes is a plausible leeway for effective engagement in the innovation process of knowledge generation and diffusion because it enables the creation of new windows of opportunity. Investment in minor modifications may boost the creation of an absorptive capacity, leading to a reduction in the gap between the existing competences and those required to effectively generate new knowledge from the exploitation of foreign technology, for example in the form of imported higher technology content capital goods. Once a sufficient absorptive capacity is developed foreign knowledge would then, and only then, be expected to enhance competence creation in developing countries. Our analysis confirms that a tight link does indeed exist between innovation-led growth and competence building, and the link is important in taking advantage of the opportunities that arise from technological transformations.

Our view concurs with previous findings including those of an empirical study carried out by Devarajan, Easterly & Pack (2001), which concluded that importation of higher technology capital lead to a fall in labour productivity in Tanzania due to the absence of a sufficient absorptive capacity. The particular concerns of developing countries with regard to solving specific economic problems may be tackled much more feasibly through focused domestic knowledge generation and diffusion that is capable of sparking off an effective feedback mechanism between knowledge creation and interactive learning whose dynamism would subsequently develop an absorptive capacity, and eventually trigger the cumulative and interactive process that creates an interface between domestic knowledge and foreign knowledge.[9]

While the analysis in this paper has shed some light on how the learning capability impacts on the knowledge acquisition process, it may be interesting to further analyse the dynamics of catching-up and falling behind with the aim of gaining some understanding of how time continuously runs out against lagging countries, leading to a situation of quasi-permanent and accelerated divergence with industrialised countries.

[9] For empirical evidence see for example Wamae, W. (2006) "Are north-south technological spillovers substantial? A dynamic panel data estimation,

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