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Information Transmission and the Bounds to Growth

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Abstract

This paper studies the long run growth implications of the presence of information acquisition and transmission costs. We assume that vertical innovation requires researchers to be informed on the current version of the product they want to improve upon; and we also assume that quasi-fixed managerial inputs are required for production in the manufacturing sector. Despite the fact the increases in total factor productivity cause R&D and managerial quasi-fixed labor costs to decrease in the same way as variable labor costs, the presence of these costs is sufficient to rule out the strong scale effect at all levels of the intertemporal returns to ideas. More importantly, the upper bound of long run growth rates crucially depends on information transmission costs.

KEYWORDS: R&D and Growth, Information and Communication Technologies, Scale Effect

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1. Introduction

Recent literature in microeconomic theory argues that, within large firms as well as among different firms, "information processing constraints limit centralized decision making" (Radner and Van Zandt 2001, p. 551). More specifically, firm tasks "use soft information that must be substantiated in lengthy reports, and the process of reading reports, understanding the information, drawing conclusions, and communicating these conclusions to others is difficult and - most importantly - it takes time" (p. 547).

We formalize the impact of information processing costs and management input costs in a simple macroeconomic growth model. In particular, our work differs from much of the previous growth literature in that we incorporate three assumptions about innovation and production:

1) Purely creative activities are fundamentally different from mechanical information acquisition and transmission. In particular, we will assume that the production function for purely creative activities can be improved by technological change in a very general way.

2) Vertical R&D activity requires labor costs for research workers to remain informed about the current state of technical knowledge. Technological change can improve this "information processing" technology.

3) Managerial work requires administrative and supervision labor costs.

Our first assumption is motivated by our desire to avoid imposing too much structure on the way past ideas are expected to affect future ideas invention. Since Romer's (1990) seminal paper, the stock of existing ideas is assumed to exert a highly specified intertemporal externality on current and future inventive abilities, positive in most cases, negative in others (as, for example, in Segerstrom 2000). However in our model the long run effect of already discovered goods and methods on researcher creativity and imagination is maintained as general as possible.

Assumption 2 is motivated very simply within Schumpeterian growth theory (Aghion and Howitt 1998) by the consideration that pure entrepreneurial activity consists of inventing entirely new ways to meet unsatisfied consumer or producer needs (horizontal innovation) whereas purely inventive vertical R&D activity consists of discovering non-trivial improvements on existing goods (vertical innovation). Since vertical researchers need to know what version of the product they are trying to improve upon they need to be constantly updating themselves on what is going on at least in their own sector. Moreover we consider not only the problems tied to information transmission but also the information acquisition costs for both researchers and firm managers, as argued by Garicano (2000).

The existence of costs necessary for information transmission and acquisition is recognized also by Cohen and Levinthal (1989, p.570), who maintain: "When economists do think about the costs of knowledge transfer, they typically identify them with immediate information processing or imitation costs. In suggesting that technological knowledge is a public good, Arrow and others do not deny the existence of such costs, but argue that they are typically small relative to the cost of creating new knowledge." Cohen and Levinthal (1989, 1990) develop the 'absorptive' capacity concept, by which the authors mean "… the firm's ability to identify, assimilate, and exploit knowledge from the environment…".[1] As argued by the authors the basic element of the absorptive capacity of firms is prior knowledge which includes not only basic skills and a shared language "…but may also include knowledge of the most recent scientific or technological developments in a given field."[2]

Moreover "…prior knowledge permits the assimilation and exploitation of new knowledge. Some portion of that prior knowledge should be very closely related to the new knowledge to facilitate assimilation, and some portion of that knowledge must be fairly diverse, although still related, to permit effective, creative utilization of the new knowledge."[3] Hence the 'absorptive' capacity concept developed by Cohen and Levinthal (1989, 1990) envisages prior knowledge as the necessary background for each effective R&D effort conducted by the existing

[1] Cohen and Levinthal (1989, p.569).
[2] Cohen and Levinthal (1990, p.128).
[3] Cohen and Levinthal (1990, p.135). The authors mean that the R&D efforts not only contribute to developing completely new products or processes but also enhance the firm's ability to assimilate and exploit existing information. In our paper this means that the economywide cumulative R&D effort as represented by the existing technological level A_t^{max} tends to reduce the R&D effort dedicated to information acquisition and transmission, as represented by the factor c/ A_t^{max}. This argument will become clearer later.

research firms. As Cohen and Levinthal (1989, p.572) maintain “To the extent that findings in a field build upon prior findings, an understanding of prior research is necessary to the assimilation of the subsequent findings...the firm cannot passively assimilate externally available knowledge. It must invest in its own R&D to absorb any of the R&D output of its competitors.” It is in the spirit of such considerations that we have assumed that in order to conduct a successful research activity every researcher needs to assimilate at least a fraction of the existing state-of-the-art, thereby incurring all costs tied to information acquisition and transmission.

Assumption 3 emphasizes the aspects of business management and R&D that involve more mechanical routine tasks involving information transmission and use in everyday industrial activity. In our opinion they are naturally modeled in a way similar to the production of ordinary goods and services. It is in this sense that we borrow from the microeconomic considerations of Radner (1992, 1993), Van Zandt (1999), and Radner and Van Zandt (2001). For example, Radner (1992, 1993) and Radner and Van Zandt (2001) envisage managerial work as a primary activity in typical U.S. Corporations, and Radner (1993, p.1109) maintains that “…a reasonable estimate is that more than one-half of U.S. workers (including managers) do information-processing as their primary activity.” Radner (1992) presents data for managerial activity in U.S Corporations from 1900 to 1987. The author shows that in 1987 about 47 percent of the 81 million full time wage and salary workers in the U.S. were engaged in occupations that probably formed part of the activity of managing. Moreover Radner (1992, 1993) defines managerial work as an activity which figures out what is to be done rather than actually doing it, that is Radner (1993, p.1109) describes “…’information-processing’ or the ‘managerial’ part of the firm as one huge decision-making machine, which takes signals from the environment and transforms them into actions taken by the ‘real workers’.” Unlike these papers, our macroeconomic long run growth focus suggests that information transmission and routine processing costs should be inversely proportional to the average productivity level of the intermediate good sectors.

In the next sections we will draw some aggregate implications of these considerations. In particular, we will prove that in a general class of frameworks the growth rate of per-capita output is bounded from above independently of the degrees of intertemporal knowledge spillovers. Hence productivity-adjusted information acquisition and transmission technologies play a crucial role in limiting growth. We will maintain a high level of aggregation in order to render our results transparent and to emphasize the robustness of our argument for several possible microfoundations.

The paper is organized as follows. Section 2 outlines the basic structure. Section 3 analyzes our main assumption on R&D information transmission. Section 4 introduces managerial quasi-fixed costs. Section 5 shows how these ingredients are sufficient to bound growth at all levels of returns to idea accumulation. Section 6 concludes the paper by relating our results to the "scale effect" debate in growth theory.

2. Basic Framework

Let us assume continuous time and unbounded horizon. Population growth is assumed constant and equal to g_L, $L(0)=1$ for the sake of simplicity, so population at date t will be $e^{g_L t}$.

Aggregate labor supply at date t will be $L(t)$, partitioned into fraction $L_Y(t)$ employed in the manufacturing, fraction $L_A(t)$ employed in the vertical innovation process and the remaining fraction $L_N(t)$ employed in the creation of completely new sectors. The total labor force at date t can be expressed as $L(t)= L_Y(t)+ L_A(t)+ L_N(t)$.

We follow the standard approach of adopting the Dixit-Stiglitz method of aggregating multisector intermediate manufacturing into a unique final output, by means of the constant elasticity of substitution (CES) composite function:

$$C(t)=\left(\int_0^{N(t)} Y_i(t)^{1/(1+\sigma)} di\right)^{1+\sigma} \tag{1}$$

where $N(t)$ denotes the mass of intermediate goods already introduced into the economy at date $t \geqslant 0$, $Y_i(t)$ is the production of variety i at date t, and $\sigma>1$ is inversely related to the elasticity of substitution among intermediate products. Let each variety $Y_i(t)$ be produced according to a constant returns to scale production function

$$Y_i(t) = A(t) L_{Yi}(t)^{\alpha} X_i^{1-\alpha} \tag{2}$$

with X denoting the fixed factor (land) whose total supply is normalized to 1, $L_{Yi}(t)$ is labor engaged in the production of the variety i at date t, and total factor productivity index $A(t)$ captures in a synthetic way the stock of vertical innovations accumulated up to date t. Concentrating on symmetry we assume $L_{Yi}(t)=L_Y(t)$, $X_i=X$, and hence $Y_i(t)=Y(t)$, $\forall i$. Therefore we can write the aggregate final output as

$$C(t)=Y(t)=N(t)^{\sigma}A(t)X^{1-\alpha}L_Y(t)^{\alpha}. \tag{3}$$

3. Knowledge Accumulation

New ideas are produced using as inputs labor and the stock of ideas– summarized by the per-sector productivity level and the number of sectors – which are accumulated over time with the first being paid for and the second being common property. In this section, by applying to the R&D technology the mechanics of information transmission analyzed by Radner (1992 and 1993) and Radner and Van Zandt (2001) as well as applying the learning cost considerations of Garicano (2000), we easily get to powerful implications about the evolution of productivity.

In the existing literature the innovative activity benefits from the intersectoral knowledge spillover so that each researcher gets immediately informed, without any effort (or "waste of time"), about the evolution of the general knowledge frontier. As remarked by Aghion and Howitt (1998) and Howitt (1999), and Segerstrom (2000) innovation in one sector is better viewed as the successful adoption of general knowledge advancement produced as a byproduct of the whole economy's innovative efforts. We adopt this view of the innovative process, but we postulate that R&D units need to keep updated about the ongoing recent advances by spending a proportional labor cost. As remarked by Van Zandt (1999, p.634), " in reality, individuals are bounded not so much by the total amount of information processing they can handle, as by the amount they can perform in a *given amount of time*. Furthermore, the problem when making decisions is not simply to use a lot of information, but also to use *recent* information." In the same spirit, Garicano's (2000) view of learning costs due to learning the solutions to the problems faced by each worker, in our case R&D and management workers.[4]

In our model we adopt this microeconomic foundation for information acquisition assuming that each researcher needs to spend time and/or effort to keep updated with at least a minimal fraction of the recent new information (new ideas). Empirical evidence indirectly in favor of our assumption can be found for example in Hicks' et al. (2001, Fig. 8, p. 698) thorough analysis of US patent citation data. For each industrial patent they compute the median age of the patents cited in the 1994-1998 period, and find that it ranges from about 15 years in Aerospace, Textiles and Paper production to about 6.5 years for Computers, Telecommunications, Semiconductors and Electronics. They also compute the median age of cited scientific papers and find a more concentrated distribution (ranging between 6 and 11 years), with most sectors' patents citing scientific papers of about 9 years median age.

Our model's updating labor cost is proportional to gathered information, but is inversely proportional to the economy-wide total factor productivity level. More specifically, in our framework we will assume that the evolution of the economy-wide technology $A(t)$ obeys the following equation:

$$\dot{A}(t) = \varphi[A(t), N(t)] L_A(t) Max\left[\left(1 - c\frac{\dot{A}(t)}{A(t)}\right),\ 0\right] \tag{4}$$

where $\varphi[A(t),N(t)]$ is any real and positive function that captures the productivity of the accumulated knowledge stock in the improvement of productivity, $L_A(t)$ is the fraction of total labor force $L(t)$ working in R&D, and $c/A(t)$ is a positive flow labor unit cost of keeping oneself updated about the latest innovations. In fact – in a discrete approximation interpretation – $c/A(t)>0$ - labor units have to be sunk in order to try to

[4] As Garicano (2000, p. 878) maintains: "Workers can learn the solutions to the problems they confront at a cost. I assume that the cost of learning an interval A of problems is proportional to the size of this interval, $\mu(A)$ (its Lebesgue measure), and call the constant per period unit learning cost c. For example the cost of learning all problems in the interval $[0,Z]$ is cZ."

adopt each general technological improvement to the sector in which the researcher operates. Every time new technological improvements occur at the economy-wide level, Howitt's (1999) and Segerstrom's (2000) sectoral adoption problem becomes a new one, which means that a second vertical R&D labor sunk cost has to be incurred. The sequence of successive sunk R&D labor costs per unit time is equal to the number of such sunk labor costs times the number of general technological improvements being aimed at per unit time: this becomes a quasi-fixed flow cost for each researcher's vertical R&D.

It is worthwhile noting that equation (4) captures the notion that the faster the technological frontier expands, the more flow labor effort is necessary to assimilate it, but at the same time the higher the already acquired general knowledge the easier the acquisition of new information. In fact, given the already reached level of the transmission technology, monitoring a double information flow imposes double monitoring time, but advances in information and communication technologies[5] make it easier to transmit and to scan a larger mass of information per-unit time. Hence it seems quite natural to assume that quasi-fixed R&D input requirements in the information transmission process decrease in the same proportion as do the manufacturing input requirements.[6]

It is important to remark that we are not even assuming that R&D workers need to know *all* relevant innovations in their field in order to have a positive probability of innovating. Parameter $c>0$ can capture any fraction of the flow of innovations that it is necessary to know. It may well be that such a fraction is as small as one thousandth or less:[7] in so far as there is a

[5] Such as for instance the Internet general purpose technology.

[6] Such an effect of technology frontier improvements on information acquisition by the researchers is also maintained by Garicano (2000, p. 890) who writes "…the cost of acquiring knowledge (c), as understood here, is affected by changes such as the introduction of expert systems and electronic diagnostics: each worker can solve, for a given investment in acquiring knowledge, a larger proportion of problems. For example, a machine operator can solve more problems for a given investment in learning if the machine is fitted with a diagnostic system." Moreover the same author adds (p. 899): "The evidence seems consistent with the interpretation that information technology has allowed workers cheaper access to knowledge (a decrease in c)…"

[7] Though it seems rather unrealistic that an engineer who knows up to Pentium II's microprocessor will have any hope in inventing a microprocessor better than a Pentium 2001th's.

minimum level of updating that is strictly necessary for innovation our argument applies.

According to our theory the knowledge accumulation and diffusion process can be separated into two components: 1) information transmission and acquisition, viewed as an activity more akin to manufacturing production because it takes place in a rather mechanical fashion; 2) the purely innovative activity requiring particularly creative capacities and thereby following a more complex dynamics.

In accordance with this view, the information acquisition and transmission moment is assumed to remain pegged by the evolution of the manufacturing productivity level *A(t)*.

The "purely innovative activity" in developing countries often – though not always - consists in the learning and adaptation to local conditions of technologies invented elsewhere. In such a case it is very natural to assume that the intertemporal learning spillover might be different from that of the leading-edge countries, because the researchers are doing qualitatively different kinds of activities. Therefore we believe that a positive feature of our formulation is the high degree of generality of function $\varphi(.)$. The inspiration that local researchers get from foreign knowledge stocks is potentially complicated and heterogeneous from culture to culture, whereas the mechanical information transmission of new knowledge or new adoption flows respond in the same way to general industrial productivity nearly everywhere. Hence we believe that our formulation of R&D seems to fit also a development context in a flexible enough way as to include several different applications.

Solving (4) for $\frac{\dot{A}(t)}{A(t)}$ we get:

$$g_A(t) \equiv \frac{\dot{A}(t)}{A(t)} = \frac{1}{\frac{A(t)}{\varphi[A(t), N(t)]L_A(t)} + c} \tag{5}$$

Then the growth of knowledge is bounded from above by a constant value, and we can state the following condition

$$g_A < \frac{1}{c} \tag{6}$$

This holds regardless of the degrees of intertemporal spillover and regardless of the economy's being at a steady state or out of it. Moreover, since the economy's growth rate is always lower than $1/c$ in principle our result allows both for endogenous and for exogenous growth depending on the microeconomic foundations adopted in a more complete model.

4. Product Varieties and Quasi-Fixed Manufacturing Costs

As in Romer (1990), Howitt (1999) and Segerstrom (2000), in our framework the number of intermediate good sectors is constantly enlarging as a result of horizontal innovation. Unlike these papers, we assume that each intermediate good production technology requires a quasi-fixed cost $b/A(t)$ to be operated. For example, in each intermediate good firm a minimum amount of managerial labor per production period is necessary, but that amount is inversely proportional to the economy-wide productivity level.

Hence we could think that in each firm a minimum amount of managerial work as described by Radner and Van Zandt is necessary to operate it in each production period. Furthermore we assume that productivity improvements decrease this quasi-fixed cost as they likewise do in manufacturing. As Garicano (2000, p.898) writes "[f]irst, expert systems and codification allowed by computers reduce the cost of acquiring the knowledge necessary to solve a given proportion of possible problems. … such an expert system would increase the ratio of production workers to problem solvers…the theory presented here predicts that reductions in the cost of communicating knowledge also increase the proportion of production workers to problem solvers…"

In the spirit of Schumpeter's view of the introduction of completely new – at least to the country that is introducing them - goods, we think it natural to assume that the horizontal innovation process requires "entrepreneurial ability" and ingenuity. At the same time, we assume that in order to produce any existing good each firm has to incur in a quasi-fixed cost consisting, for example, of minimum managerial work per production period. Because also this activity, as Schumpeter (1942) maintains, is a routine activity and hence it is more akin to the manufacturing activity, we assume that it can be improved over time by technological progress as the manufacturing and updating activities of the country. The same is not valid for the inventive component inherent to the creation or the adaptation of completely new varieties, in this case the Schumpeterian "entrepreneurial ability" is more complex and tied to the personal ability of each individual.

The new goods are introduced per unit time according to

$$\dot{N}(t) \leq f[N(t), A(t)]Max\left[L(t) - N(t)\frac{b}{e^{g_A t}};0\right] \qquad (7)$$

where we have assumed that *A(0)=1*. Function *f(.)* is any positive function that captures the type of dynamic returns existing in the creation of new varieties of goods, i.e. new sectors and market niches. We shall show how our analysis holds for any dynamic returns in the horizontal innovation process, that is both for positive and negative externalities exerted by the existing number of varieties at date t and by their productivity level to the flow of completely new goods introduced per unit time. Notice that if (7) holds the upper bound for the new variety creation rate:

$$g_N(t) \equiv \frac{\dot{N}(t)}{N(t)} \leq f[N(t), A(t)]Max\left[\frac{L(t)}{N(t)} - \frac{b}{e^{g_A t}};0\right] \qquad (8)$$

Hence (8) implies that asymptotically $N(t) \leqslant [L(t)/b] \bullet e^{g_A t}$, and finally (dropping time indexes for notational simplicity):

$$g_N \leq g_A + g_L \,. \qquad (9)$$

5. Long Run Growth

From the labor market equilibrium condition we can express final output (3) as

$$Y(t) = N(t)^{\sigma} A(t) X^{1-\alpha} \left(L(t) - L_A(t) - L_N(t)\right)^{\alpha} \qquad (10)$$

From eq. (10) and after recalling eq. (6) on the growth rate of productivity and eq. (9) on the rate of new sector introduction, we easily obtain the following upper bound of the per capita consumption growth rate:

$$g_{\frac{Y}{L}} \leq \sigma g_N + g_A - (1-\alpha) g_L \leq \frac{1+\sigma}{c} + (\alpha + \sigma - 1) g_L \tag{11}$$

Notice that measure (11) of the upper limit of per capita consumption is independent of functions *φ(.)* and *f(.)*.

6. Discussion of the Results

Since Jones (1995) the attempts to remove the early endogenous growth theory's prediction of a "strong scale effect" (Jones 2003) from the theoretical models have been important in highlighting several neglected aspects of the R&D process. The most well known ways out of the scale effect point to an "increasing complexity" effect and/or to a "R&D dilution" effect (see Dinopoulos and Thompson, 1999 and Jones, 1999 for useful reviews). In this paper we have performed an exercise that hopefully casts additional light on other aspects of the growth mechanics that may be useful in removing the scale effect and that seems to have been neglected so far. For example Romer's (1990) prediction of a scale effect of population size on asymptotic per capita GDP critically hinged on the assumption that at all levels of technology a unit amount of labor could be able to run an infinite number of firms. Our model proves that if we relax this assumption in favor of the assumption that a unit amount of labor could be able to run a number of firms increasing in proportion to the economy-wide labor productivity the asymptotic scale effect disappears from this class of models.

Taking account of the information acquisition and transmission technology in a way that parallels manufacturing production technology implies that the growth rate of per-capita output is limited above for all degrees of intertemporal spillovers. We claimed that in order to improve the quality of an existing good researchers have to spend time in getting informed about at least a minimal fraction of the most recent qualities, with information acquisition technology benefiting from productivity advances in the same way as finite goods and services. Moreover we assumed that managerial labor productivity also grows at the same rate.

From these assumptions it follows that the flow of vertical innovations cannot increase more than proportionally to its cumulated stock and the number of sectors in the economy cannot grow more than proportionally to its cumulated stock.

6.2 Equilibrium Growth in the Absence of Population Growth

Is equilibrium growth sustainable in the absence of population growth? In our model, this depends on the particular specification adopted for our general functions $\varphi(.)$ and $f(.)$. It is likely that in some cases steady states cannot even exist and the growth rates would keep oscillating between the extremes laid out in this paper. Without taking into consideration variety expansion, one could sketch an example[8] with $\varphi=A^{\theta}$ and obtain semi-endogenous growth if $0<\theta<1$: as in Jones (1995), as a larger and larger stock of ideas accumulates it would become more and more difficult to find new ideas that have the same *proportional* impact on productivity. Hence at zero population growth rate the productivity growth rate in manufacturing would tend to zero. What's more, from our eq. (4) it follows that even a very high population growth rate would not suffice to make A grow at a rate larger than $1/c$. Hence our implications can be even less "endogenous" than Jones' (1995).

On the other hand, if $\theta \geq 1$ eq. (5) would become

$$g_A(t) \equiv \frac{\dot{A}(t)}{A(t)} = \frac{1}{\frac{1}{A(t)^{\theta-1} L_A(t)} + c} \tag{5b}$$

If $L_A(t) \geqslant l > 0$ - with lower bound l no matter how small - that is if the amount of labor allocated to vertical R&D is uniformly bounded away from zero, eq. (5b) implies that

$$g_A(t) \equiv \dot{A}(t)/A(t) \rightarrow 1/c$$

monotonically from below. Hence steady state per-capita growth rates only depend on productivity-adjusted information transmission costs.

[8] Also see Cozzi (2003).

Though also in this case growth is not "endogenous", sustained growth is possible without the strong scale effect, despite zero population growth.

6.3 Endogenous or Semi-Endogenous Growth?

In all existing solutions to the strong scale effect the innovative performance of the economy is endogenous, at least in the sense that it responds to industrial and R&D policy. In the models adopting the increasing complexity arguments this shows up in levels (of either aggregate income or welfare), whereas in models in which variety expansion is proportional to population this shows up in growth rates. Key to the different results is whether or not the model builder believes that a recently discovered idea has the same proportional impact on their sector's manufacturing productivity as it had an idea discovered, say, 100 years ago. Moreover, it is far from granted that an engineer working today would be able to solve the same (impact adjusted) number of problems that are still open today any better than an engineer did a 100 years ago for the problems of her/his time. In this respect, Jones (1995) and Segerstrom's (1998) models are very optimistic about researchers' productivity.

Depending on the intertemporal spillover assumption one can have endogenous growth rates or not, as well known in the literature. What is the contribution of our paper to this debate? Since we added a bound on growth we certainly cannot overturn the semi-endogenous implications of models adopting increasing complexity. Indeed, we strengthen their implications, as we reduce the role of fertility on growth rates. In the other extreme, stronger intertemporal spillovers do not help the growth rate to overpass the threshold given by eq. (11). What could happen below that threshold is not easy to ascertain, because depending on the specific functional forms adopted we could have unsteady growth. This is a line of research to be developed in future studies.

Throughout this paper we held constant productivity-adjusted transmission and management costs, whereas perhaps in a more realistic extension they could be affected by collective action, thereby recovering endogenous growth. Information and communication technologies (ICT) could be helped to overcome some of their market failures: this paper suggests that successful industrial policies for enhancing ICT would have very strong implications for long lasting growth and for catching up with development. Similar effects could be obtained by better organizational forms, designed to improve information transmission both at the R&D level and at the managerial level. In so far as public policies could help achieve these goals the bounds to growth might be predicted to be endogenous.

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