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# KNOWLEDGE EXHAUSTIBILITY AND SCHUMPETERIAN GROWTH

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# KNOWLEDGE EXHAUSTIBILITY AND SCHUMPETERIAN GROWTH [1]

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**ABSTRACT.** This paper accommodates the new understanding of the limited exhaustibility of knowledge into the Schumpeterian frame of the creative response to articulate a comprehensive model of Schumpeterian growth. The limited exhaustibility of knowledge and its transient appropriability favor the accumulation of a stock of quasi-public knowledge. The increasing stock of quasi-public knowledge together with appropriate knowledge governance conditions account for the secular decline of knowledge costs and the increase of diachronic and pecuniary knowledge externalities. Because of its limited exhaustibility and the consequent accumulability, knowledge is an endogenous endowment that accounts for growth. Unexpected out-of-equilibrium conditions in product and factor markets stir the response of firms. The availability of knowledge externalities accounts for the rate of innovation as they help making the reaction creative so as to enable the introduction of innovations. The search for technological congruence and the secular decline of the cost of technological knowledge accounts for its knowledge intensive direction as it induces the introduction of biased technological changes that augment the output elasticity of knowledge as an input. The limited exhaustibility of knowledge accounts for the secular trend towards the knowledge economy.

**KEY WORDS: KNOWLEDGE LIMITED EXHAUSTIBILITY AND CUMULABILITY; KNOWLEDGE AS AN ENDOGENOUS ENDOWMENT; DIACHRONIC KNOWLEDGE EXTERNALITIES; KNOWLEDGE COSTS; SCHUMPETERIAN CREATIVE RESPONSE; INDUCED TECHNOLOGICAL CHANGE; TECHNOLOGICAL CONGRUENCE.**

**JEL CODE: O33**

## 1. INTRODUCTION

Recent advances of the economics of knowledge have enabled to identify, next to its limited appropriability, a second and most important characteristic of knowledge: its limited exhaustibility of knowledge. The appreciation of the limited exhaustibility of knowledge and the reappraisal of the Schumpeterian framework of the creative response enable to articulate a comprehensive model of Schumpeterian growth based upon the endogenous accumulation of an input. The flows of knowledge generated at each point in time to fuel oligopolistic rivalry can be fully appropriated by

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‘inventors’ albeit for a limited stretch of time. Eventually in fact, after a short period of appropriation, all the new knowledge becomes public and adds to the stock of public knowledge. At each point in time the system is in equilibrium as the marginal productivity of knowledge matches its costs. In the long term, however, the increase of the size of the stock of public knowledge leads –for given levels of the knowledge governance mechanisms in place within the economic system- to the reduction of its cost as an input into the production of all the other goods. Because of its limited exhaustibility knowledge is an endogenous endowment that accounts for growth[2].

The role of the accumulation of knowledge as an endogenous endowment in accounting for growth is magnified by the Schumpeterian framework of the creative response. Following Schumpeter (1947) mismatches in factor markets and unexpected out-of-equilibrium- performances stir the creative reaction of firms. The reaction is creative, so as to lead to the introduction of innovations, when knowledge externalities are available. The search for technological congruence induces the search for directed technological changes aimed at increasing the knowledge intensity of the technology production function. The increased knowledge intensity of the production process favors the accumulation of new knowledge. At each point in time new proprietary knowledge can be appropriated. Eventually, however, it spills and adds on to the stock of public knowledge. The increasing stock of public knowledge yields pecuniary externalities that feed the creative reaction of firms, the generation of additional knowledge and the introduction of further innovations. The motion of the system rests upon the laws of accumulation of knowledge, its effects on the cost of knowledge and the induced search for technological congruence. As long as the accumulation of knowledge is sufficient to contrast the increase of its costs stemming from the shift of its derived demand, and the quality of the knowledge governance mechanisms does not deteriorate, growth is sustainable.

The rest of the paper is structured as it follows. Section 2 reviews briefly the foundations of the limited exhaustibility of knowledge and recalls the Schumpeterian framework of the creative response. Section 3 presents a simple model of endogenous economic growth based upon the interplay between knowledge externalities in the knowledge generation function and the increasing supply of technological knowledge, and the reduction of the relative user costs of technological knowledge in the technology production function with the consequent induced introduction of knowledge intensive technological change. The conclusions summarize the main findings

## 2. KNOWLEDGE EXHAUSTIBILITY AND THE CREATIVE RESPONSE

[2] The limited exhaustibility of knowledge and its intertemporal accumulation -very much like the accumulation of savings into the stock of wealth- contrasts the notion of a stable equilibrium and forces to take into account the role of endogenous endowments in the theory of growth (Antonelli, 2016).

The implementation of the Arrovian analysis of knowledge as an economic good enables to identify, next to its classical attributes such as the limited appropriability, non-excludability and non rivalry in use, also its limited exhaustibility with the important implications in terms of diachronic cumulability and synchronic complementarity (Arrow, 1962 and 1969, Antonelli, 2017b and 2018). The limited exhaustibility of knowledge has important implications for its use as an input in the production of all the other goods and for its generation. The introduction of the technology production function helps appreciating the role of technological knowledge as a distinctive and indispensable input –next to capital and labor- into the production of all the other goods. The introduction of knowledge generation function helps to appreciate the role of technological knowledge as the output of a dedicated and intentional economic activity into which existing knowledge is an indispensable input as well as an indispensable input (Griliches, 1979). The generation of technological knowledge consists in the recombination of existing knowledge items (Weitzman, 1996; Arthur, 2009). The generation of knowledge is a branching out process where new technologies are generated building upon the existing ones (Fleming and Sorenson, 2001). As a consequence the recombinant knowledge generation is a process with clear non-ergodic characteristics: at each point in time the rate and the direction of the process are influenced by the stock of the existing knowledge (Antonelli, 2008 and 2017b).

At the firm level the intrinsic non-excludability of knowledge limits its appropriability: knowledge producers can retain the command of their 'inventions' only for a stretch of time. Knowledge appropriability is limited because it is transient: proprietary knowledge gradually, but inevitably, leaks out, spills and is eventually disseminated in the system. Because of knowledge non-exhaustibility and cumulability, the flows of knowledge spilling from 'inventors' at each point in time add on to the stock of knowledge. At the firm level, knowledge transient appropriability impedes its exclusive cumulativity intramuros (Griliches, 1979).

At the system level, instead, knowledge non-exhaustibility and cumulativity display instead, their powerful effects. The flows of new knowledge –with appropriate lags stemming from the duration of appropriation by inventors- add on to the stock of public knowledge and engender diachronic knowledge externalities.

At each point in time the new vintages of knowledge -generated by means of the flows of R&D activities- add –with a delay due to the dissemination lags- to the public stock of knowledge that keeps increasing. The accumulation of the stock of quasi-public knowledge may affect the cost of knowledge provided that effective knowledge governance mechanisms are kept in place, but it is not the single factor. The cost of knowledge in fact is heavily influenced by its transmission (Arrow, 1969) and absorption costs (Cohen and Levinthal, 1990) that are determined by the quality of the knowledge governance mechanisms that affect the quality of the knowledge connectivity of an economic system. The changes in the quality of knowledge governance mechanisms and the consequent changes in the knowledge transmission and governance costs may compensate or magnify the effects of the increasing size of the stock of knowledge (Antonelli, 2017b).

The quality of knowledge governance mechanisms in place and the levels of knowledge connectivity of the system into which firms are embedded are most important. Systems with high levels of knowledge connectivity are able to integrate the different knowledge items that are generated at each point in time into an effective stock of knowledge. The high levels of knowledge connectivity enable the agents to access and use the knowledge items available in the stock of quasi-public knowledge at low costs: pecuniary knowledge externalities are large. Systems with low levels of connectivity are not able to pull together the different knowledge items that remain dispersed into the system. The stock of knowledge is public but fragmented and its costs of accessing and using it are much higher: pecuniary knowledge externalities are low. In systems with high levels of knowledge connectivity knowledge externalities are high. In systems with low levels of knowledge connectivity, knowledge externalities are low. Knowledge externalities are endogenous and diachronic (Antonelli and Ferraris, 2018).

Diachronic knowledge externalities are determined by three dynamic processes: i) the accumulation of the stock of quasi-public knowledge affects the structure of the endowments of the system. Knowledge is an endogenous endowment that, because of its limited exhaustibility and consequent accumulation, becomes larger and larger. ii) the unit costs of the stock of quasi-public knowledge is >0. The access and use of the knowledge items that pile up in the stock of quasi-public knowledge in fact is not free: it requires relevant transmission and absorption costs that are necessary to search, screen, identify, uncode and recode, and finally use the specific knowledge items that are necessary for the recombinant generation of new knowledge. It seems plausible to assume that, for given levels of knowledge governance quality, the unit costs to accessing and using the stock of knowledge decline together with its size. The larger the stock and the lower the search activities that are necessary to identify the relevant knowledge items. iii) The general levels of knowledge absorption and transmission costs depend upon the quality of the knowledge governance mechanisms that each economic system is able to implement. The quality of the structures of knowledge interactions and transactions that qualify the connectivity of the system enable to access and use the stock of quasi-public knowledge is itself endogenous and does not necessarily stay put. It may decline as well as improve. .

As a consequence, assuming that the quality of knowledge governance does not decline, the larger is the endogenous stock of knowledge and the lower is its cost both as an input into the knowledge generation process, and an input in the technology production function. Following Griliches (1979) and Weitzman (1996) the stock of quasi-public knowledge enters the recombinant knowledge generation function, next to other inputs such as current R&D expenditures. In sum, the larger is the stock of quasi-public knowledge as an input and the larger the knowledge output, *consequently,* provided that the unit cost to accessing and using it declines together with its size, the lower are the levels of knowledge costs that fall lower and lower below the equilibrium levels that would take place if knowledge were a standard economic good with substantial exhaustibility.

If the quality of the knowledge governance mechanisms and consequently the levels of knowledge connectivity decline the increase of the costs of absorption and transmission of knowledge may offset the effects of the increasing size of the stock of quasi-public knowledge. The dynamics of the system is blocked.

If the quality of knowledge governance mechanisms does not decline over time, and the unit costs of accessing and using the –increasing- stock of quasi-public knowledge decrease, the generation of technological change takes place with knowledge costs that decrease along with the inter-temporal increase of the stock of knowledge and become lower and lower than equilibrium levels.

The appreciation of knowledge exhaustibility and its consequent cumulativity at the system level enables to grasp its crucial role as an endogenous endowment that keeps increasing because of its special properties so that its actual costs falls lower and lower, below the levels of standard economic goods. A system characterized by the endogenous accumulation and declining cost of a basic endowment –such as knowledge and wealth- cannot reach a stable equilibrium (Antonelli, 2016).

The integration of the cumulative dynamics of knowledge as an endogenous input into the Schumpeterian framework of the creative response provides important insights and makes the case of persistent out-of-equilibrium even stronger. The Schumpeterian framework of the creative response has been somewhat neglected by the literature. Recent contributions have called attention on its merits (Antonelli, 2008 and 2017a). The contribution of Schumpeter (1947) can be considered a major attempt to synthetize the different ingredients laid down in his previous work. Firms are exposed to frequent mismatches between expected and actual conditions of product and factor markets. They can react either by means of adaptive responses or creative responses. Adaptive responses consist in price and quantity adjustments by means of technical changes within the given technology on the existing map of isoquants. Creative responses consist in the introduction of new technologies that change the existing map of isoquants. Adaptive responses take place when firms have not access to the necessary externalities. Creative responses are possible when firms can take advantage of externalities and specifically knowledge externalities that make possible the generation of new technological knowledge and the eventual introduction of innovations.

This approach seems able to accommodate in a single and powerful framework of analysis the so-called induced technological change approach (Ruttan, 2001). Technological change is intrinsically biased and far from neutral. It consists in the introduction of new technologies directed at increasing the output elasticity of inputs that are relatively cheaper in the factor markets (Acemoglu, 1998, 2015). The larger is the technological congruence and the larger is output (Antonelli, 2017a and b). The direction of technological change depends on the conditions of factor markets. Firms active in labor (capital) abundant factor markets have a clear incentive to introduce labor(capital)-intensive technological change. The search for technological congruence is likely to favor the direction of technological change towards the introduction of more knowledge intensive technologies in factor markets characterized by the low and decreasing costs of knowledge. The sequential search for technological congruence pushes the direction of technological change to take into account the endogenous increase of the knowledge endowment and the consequent dynamic reduction of the costs of technological knowledge and favors the eventual introduction of more knowledge-intensive technologies.

Let us now try to pull these converging threads together. The creative response framework is reinforced by the integration of the understanding of the dynamics of non-exhaustible knowledge as an endogenous endowment so as to articulate a spiraling process that may last as long as the quality of knowledge governance mechanisms and the levels of knowledge connectivity of the system support the reduction of the costs of knowledge and the levels of knowledge externalities. Because of the successful creative response new mismatches between expected and actual market conditions take place both in the product and in the factor markets. The Schumpeterian creative response sustains additional flow of R&D expenditures. The consequent accumulation of stock of public knowledge causes –for constant levels of the quality of knowledge governance mechanisms, the inter-temporal fall of the price of knowledge and the increase of the levels of diachronic pecuniary knowledge externalities. The search for technological congruence induces the introduction of knowledge intensive technological innovations.

In the long term the increasing amount of knowledge externalities and the reduction of knowledge costs supports the creative reaction of firms and induces the introduction of biased technological changes directed to the introduction of knowledge intensive technologies that in turn leads to the accumulations of even larger stock of public knowledge stocks. The search for higher levels of technological congruence and the new direction of technological change aimed at increasing the matching between the declining costs of technological knowledge and its increasing output elasticity accounts for self-sustained Schumpeterian growth.

The knowledge intensive direction of technological change can account for the shift of industrialized economies to knowledge economies characterized by the large output elasticity of knowledge as an input and the specialization of advanced countries in the generation and use of technological knowledge as both an output and input. The growth path is interrupted when the shift of the derived demand for technological knowledge has a 'positive' impact on the cost of technological knowledge that is larger than the 'negative' effects of diachronic knowledge externalities stemming from the joint effects of knowledge non exhaustibility, cumulativity and transient appropriability.

The endogenous growth model highlights the crucial role of the conditions of accumulation, access and use of technological knowledge that cannot be fully appropriated by its inventors. It enables to appreciate the systemic conditions that shape the actual costs of knowledge. It shows that there is a constraint to the self-sustained process of growth that stems from the dynamic balance between the effects of the increased derived demand of technological knowledge –determined by the knowledge intensive direction of technological change- and the effects of knowledge non-exhaustibility and the consequent cumulativity and the quality of knowledge governance mechanisms. The identification of the constraint paves the way to specify policy interventions finalized to keep the system in motion on the growth path and to avoid to falling into the trap of equilibrium.

## 3. THE MODEL

This section presents a simple model that shows the dynamics of the creative response. Let us assume that the production is realized through a technology production function characterized by the combined use of some amount F of physical factors (for example, capital and labour), and some level of technological knowledge T. Their elasticity to the output are respectively $1-\delta$ and $\delta$, so that the level of output produced is:

(1) $Y = F^{1-\delta}T^{\delta}$.

Denoting with *z* and *u* the price of factors *F* and *T*, the total cost equation is:

(2) $C = zF + uT$

We assume that firms chose to keep total costs fixed and maximize the output. Formally, firms choose the values of *F* and *T* so as to solve the following problem:

(3) $$\max_{F,T} Y = F^{1-\delta}T^{\delta}$$
$$\text{s.t. } zF + uT \leq \tilde{C},$$

where $\tilde{C}$ is the constant level of cost entailed by the production.
The marginal rate of technical substitution between *F* and *T* is:

(4) $\frac{\partial Y/\partial T}{\partial Y/\partial F} = \frac{\delta F}{(1-\delta)T}$.

Firms select the equilibrium mix of inputs by imposing the ratio between the input marginal costs equal to the slope of isoquants. The equilibrium conditions for the couple of factors *F-T* is thus obtained by imposing (4) equal to the ratio of the marginal prices of factors:

$$(5) \quad \frac{\partial Y/\partial T}{\partial Y/\partial F} = \frac{\delta F}{(1-\delta)T} = \frac{u}{z}.$$

From (5), in equilibrium it must be:

$$(6) \quad F^* = \frac{u(1-\delta)}{z\delta} T^*.$$

The optimal mix of productive factors that would entail total costs equal to $\tilde{C}$ can be obtained as the solution of the following system:

$$(7) \quad \begin{cases} F^* = \frac{u(1-\delta)}{z\delta} T^* \\ \tilde{C} = zF^* + uT^* \end{cases}$$

The solution of (7) gives:

$$(8) \quad \begin{cases} T^* = \tilde{C}\frac{\delta}{u} \\ F^* = \tilde{C}\frac{1-\delta}{z} \end{cases}$$

Substituting (8) in (1), we can express the level of output that can be achieved at the cost $\tilde{C}$:

$$(9) \quad Y^* = \tilde{C}\left(\frac{1-\delta}{z}\right)^{1-\delta}\left(\frac{\delta}{u}\right)^{\delta}.$$

Building upon the hypothesis that firms react to changes in the market price of inputs so as to improve their technological congruence we assume that the output elasticity of inputs depends on their relative price: cumulated knowledge and physical factors. In particular, we assume that, because of the search for technological congruence, firms have a clear incentive to innovate and change their technology so that, when the ratio $u/z$ lowers, $\delta$ should increase. Hence according to equation (10):

$$(10) \quad \delta = \bar{\delta}e^{-u/z} + \underline{\delta}.$$

Equation (10) implies that $\delta \in (\underline{\delta}, \underline{\delta} + \bar{\delta}]$.

Let us now evaluate the effect of a variation of *u* on the level of production $Y^*$. We can write:

(11) $dY^*/du = \partial Y^*/\partial\delta\ \partial\delta/\partial u + \partial Y^*/\partial u$

To obtain $\partial Y^*/\partial\delta$, we apply to (7) the differentiation rule $D((f(x)g(x)) = f'(x)g(x) + f(x)g'(x)$, where $x=\delta$, $f(x) = \tilde{C}[((1-\delta)\square z)^{1-\delta}]$ and $g(x) = (\delta/u)^{\delta}$

In particular, to obtain $\partial[(\delta/u)^{\delta}]/\partial\delta$, we exploit the differentiation rule $D((h(x)^{l(x)}) = h(x)^{l(x)}[l'(x)\ln h(x) + l(x)h'(x)/h(x)]$ where $x=\delta$, $h(x) = \delta/u$, $l(x) = \delta$. We proceed similarly to compute $\partial[((1-\delta)\square z)^{1-\delta}]]/\partial\delta$, where we use $h(x) = (1-\delta)\square z$, $l(x) = 1-\delta$. We thus obtain:

(12) $$\frac{\partial Y^*}{\partial\delta} = \tilde{C}\left[\left(\frac{1-\delta}{z}\right)^{1-\delta}\left(-ln\frac{1-\delta}{z} - 1\right)\left(\frac{\delta}{u}\right)^{\delta} + \left(\frac{1-\delta}{z}\right)^{1-\delta}\left(\frac{\delta}{u}\right)^{\delta}\left(ln\frac{\delta}{u}\right)\right] = \tilde{C}\left(\frac{1-\delta}{z}\right)^{1-\delta}\left(\frac{\delta}{u}\right)^{\delta}\left(ln\frac{\delta z}{(1-\delta)u}\right).$$

By substituting (9) and (6), equation (12) can be rewritten as:

(13) $$\frac{\partial Y^*}{\partial\delta} = Y^*\left(ln\frac{T^*}{F^*}\right).$$

Moreover, by deriving (9), we obtain

(14) $$\frac{\partial Y^*}{\partial u} = \tilde{C}\left(\frac{1-\delta}{z}\right)^{1-\delta}\left(\frac{\delta}{u}\right)^{\delta}\left(-\frac{\delta}{u}\right) = -Y^*\frac{\delta}{u}$$

and, by taking derivative in (10), we have:

(15) $$\frac{\partial\delta}{\partial u} = -\frac{\bar{\delta}}{z}e^{-u/z}.$$

Substituting (13), (14) and (15) into (11), we have:

(16) $$\frac{dY^*}{du} = Y^*\left(-\frac{\bar{\delta}}{z}e^{-u/z}ln\frac{T^*}{F^*} - \frac{\delta}{u}\right).$$

Given that, from (12), $\bar{\delta}e^{-u/z} = \delta - \underline{\delta}$, the previous equation becomes

(17) $$\frac{dY^*}{du} = Y^*\left(-\frac{\delta-\underline{\delta}}{z}ln\frac{T^*}{F^*} - \frac{\delta}{u}\right).$$

From the previous expression, we have that a sufficient condition for $dY^*/du < 0$ is $T^* > F^*$.

The demand for technological knowledge, from (8), is given by

(18) $T^* = \tilde{C}\frac{\delta}{u}$.

From expression (18), the demand for technological knowledge is a decreasing function of $u$ and increasing with $\delta$. Note that when $u$ decreases, $Y$ increases even without technological change.

Let us assume that technological knowledge cumulates, so that the stock available at a given time $t$, is equal to the sum of the technological knowledge that has been employed in all the previous periods. We denote with $KN_t$ the level of the stock of technological knowledge, at time $t$, and with $T_j$ the level of technology at time $j$:

(19) $KN_t = \sum_{j=0}^{t-1} T_j^*$

Following Griliches (1979) and Weitzman (1996), we assume that the generation of technological knowledge is a recombinant and non-ergodic process where the stock of existing knowledge $KN_t$ enters the knowledge generation function as an indispensable input next to current R&D activities. The flows of additional knowledge add to the stock of existing knowledge that keeps increasing. As a consequence, assuming either that the unit costs of the access and use of the stock of knowledge decrease[3], the cost of the additional units of knowledge keeps decreasing. Hence we can assume that $u_t$, the unit cost of technological knowledge as an output of the knowledge generation function at time $t$, is negatively correlated with the stock of technological knowledge $KN_t$ at the same time $t$:

(20) $du_t/dKN_t < 0$

As $T^* > 0$ for any $t$, then $KN_t > KN_{t-1}$. By (20) this might imply a process where a reduction of u ($u_t < u_{t-1}$) followed, by (10), by an increase of $\delta$ ($\delta_t > \delta_{t-1}$). If $T_t^* > F_t^*$, the reduction of u and increase of δ induces endogenously an increase of the level of production $Y$. The accumulation of technological knowledge shifts, by technological congruence, the production function toward more technological intensive techniques;

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[3] To make our argument clear, we explicit here the two postulates of our analysis: i) the unit costs of accessing and using the stock of knowledge decrease with its size. It seems plausible to assume that the amount of searching activities necessary to identify and absorb the relevant knowledge items decline with the size of the knowledge stock; ii) the quality of knowledge governance mechanisms does not decline along with the size of the stock of knowledge. We assume consequently that – with a given budget- the knowledge output increases along with the size of the stock of external knowledge.

if the level of technological knowledge in use is larger than that of physical factors, the level of production increases given the same production costs.

Note that this process can take place only if the increase in the supply of knowledge is larger than the increase of its derived demand stemming from the biased technological change directed at increasing the output elasticity of knowledge in the production function.

Moreover, when some technological knowledge is first introduced, the level of cumulated knowledge KN tends to zero and the value of u is relatively high. Still, by (18), $T^* > 0$,. This implies that a minimum amount of technological knowledge is indispensable to start any production process and, because of accumulation, its cost lowers from the high levels found at the onset.

From the analysis above, as the elasticity of technological knowledge increases because of the search for higher levels of technological congruence and the consequent introduction of new biased technologies directed towards more knowledge-intensive technologies, the intensity of technological knowledge also increases.

Let us now extend the result to a macroeconomic level. On the demand side, as $u_{t+1} < u_t$ and $\delta_{t+1} > \delta_t$, it must be (from (18) $T^*(u_{t+1}, \delta_{t+1}) > T^*(u_t, \delta_t)$. It must be noted, moreover, that over time, the derived demand of technological knowledge T shifts to the right, also because of the positive effects on Y of the decline of u.

On the supply side, the supply of technological knowledge at a given time t is assumed to be an increasing function of *u* and knowledge $KN_t$:

(21) $T_t^s(u;KN_t) = kKN_t + \varepsilon u$

with k, ε > 0.

In factor markets the equilibrium price of technological knowledge is found by balancing the demand for technological knowledge (from (18) with its supply (from (21) :

(22) $\frac{Y\delta}{u} = kKN + \varepsilon u$

Figure 1 represents the variation of the equilibrium price of technological knowledge when the demand for technological knowledge shifts to the right because of the increased levels of *Y* and $\delta$ together with the supply driven by the increase of $\delta$ from $\delta_t$ to $\delta_{t+1}$.

The accumulation of technological knowledge over time induces a decrease of u from $u_0$ to $u_1$. The reduction of u causes a right shift of the derived demand of technological knowledge. This shift will take place both with an adaptive reaction and a creative one. In the latter case it will be stronger. Let us explore the matter in detail.

The derived for technological knowledge shifts to the right, because of the positive effects on Y of the decline of u, even if firms –because of the low quality of knowledge governance mechanisms at work in their economic system, are not able to implement a creative reaction and introduce biased technological changes aimed at increasing the output elasticity of technological knowledge δ. Their adaptive reaction will consist just in changes of the production techniques on the existing map of isoquants. Yet the decline of u yields and increase of Y and hence a positive, albeit smaller, shift of the derived demand for technological knowledge.

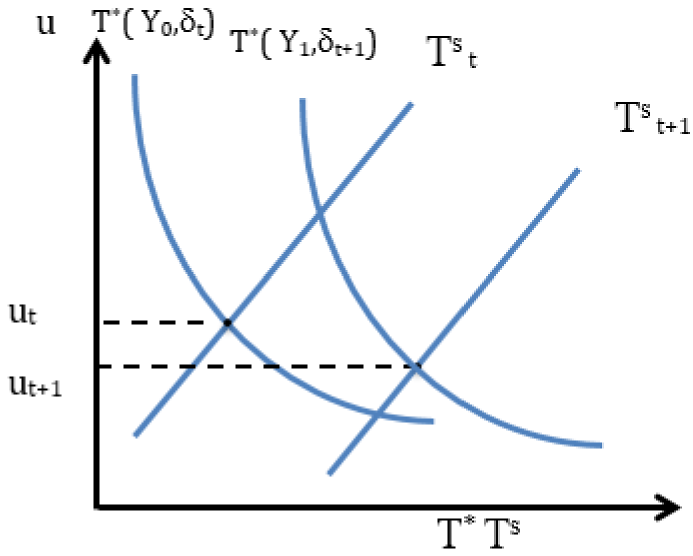


Figure 1 Equilibrium in the market for technological knowledge

When, instead, the quality of the institutional mechanisms of knowledge governance is high, firm will be able to take advantage of the reduction of u with a creative reaction and the consequent introduction of biased technological innovations. In this case the right shift of the derived demand of technological knowledge is much larger because of the twin effects of the increase of δ and the larger increase of Y caused by not only the reduction of u but also by the increase of total factor productivity.

As represented in Figure 1, when the reaction is adaptive the demand for technological knowledge shifts slightly to the right because of the increase of Y. When, instead, the creative reaction takes place, and firms can introduce directed technological innovations, $\delta$ increases from $\delta_t$, to $\delta_{t+1}$. This produces, together with the effects of the increasing levels of Y, much a larger increase of the demand for technological knowledge, shifting the relative function to $T^*(\delta_{t+1})$. On the supply side, the working of cumulativity and non-exhaustibility explains the shift of the knowledge schedule over time.

If $u_{t+1} < u_t$: the accumulation of technological knowledge sets in motion an endogenous decrease of the price of technological knowledge, leading to a process directed toward a more technology-based production mix (by means of an increase of T/F) and technological knowledge intensive- technology production function (by means of an increase of $\delta$), resulting in the long run into an increase of total factor productivity and the level of production Y.

When the supply of additional technological knowledge is not able to compensate for the increase of its derived demand the price of technological knowledge increases and the dynamics of the system stops. The need to avoid these risks identifies the scope for a dedicated economic policy aimed at implementing the dynamics of knowledge intensive technological change.

## 4. CONCLUSIONS

The paper has accommodated the new appreciation of the non-exhaustibility of knowledge within the Schumpeterian framework of the creative response. Their integration enables to articulate a Schumpeterian model of growth characterized by the dynamics of the accumulation of knowledge as an endogenous endowment and the search for technological congruence in out-of-equilibrium conditions.

The non-exhaustibility of knowledge plays a central role as it accumulates over time and pile up in a ever increasing stock as an endogenous production factor. Diachronic knowledge externalities stem from the accumulation of knowledge generated as proprietary, but appropriated by its 'inventors' only for a limited stretch of time. The current vintages of knowledge become gradually but inevitably part of the stock of public knowledge that be accessed, and used in the generation of new knowledge by every firm at decreasing costs, through time. The notion of diachronic knowledge externalities enables to reconsider the effects of the Arrovian properties of knowledge as a special economic good. The analysis of the knowledge generation process, in fact, allows to balance the negative effects of transient appropriability, in terms of missing incentives to generate new technological knowledge, with the positive effects of knowledge cumulativity and non-exhaustibility on the dynamics of the costs of knowledge. Standard economic goods are fully appropriable, but do wear and tear. The intuition of Zvi Griliches that spillovers are the other –positive- side of the transient appropriability coin is augmented and empowered by the appreciation of the inter-temporal effects of the non-exhaustibility of knowledge.

The inter-temporal accumulation of knowledge that spills, with appropriate lags, from inventors and adds to the stock of public knowledge, accounts for the decrease of the costs of knowledge as an input and hence the increase of the role of knowledge as an output. The reduction of the user cost of technological knowledge enhances the Schumpeterian –creative reaction- of firms that try and cope with the changing conditions of product and factor markets with the introduction of innovations. When the reaction, supported by appropriate levels of knowledge externalities, is creative, firms are able to search for higher levels of technological congruence that lead to foster the innovation process and to bias it towards the introduction of technological changes directed at increasing the output elasticity of technological knowledge as an input. The search for technological congruence in turn favors the accumulation of the stock of quasi-public knowledge and helps to reducing further the user costs of knowledge and the amount of knowledge externalities available within the system.

For given levels of the quality of knowledge governance mechanisms the accelerated introduction of new more knowledge intensive technologies activates a self-sustained growth process that consists in: i) reinforcing the mismatches between expected and actual product and factor market conditions, ii) pushing the generation of new technological knowledge; iii) increasing the size of the stock of existing technological knowledge, iv) reducing further the price of knowledge, v) reinforcing the levels of diachronic pecuniary knowledge externalities that vi) induce the introduction of new more knowledge-intensive technologies.

This Schumpeterian growth model highlights the crucial role of the laws of accumulation of the stock of public knowledge and of the quality of the knowledge governance mechanisms that determine the knowledge connectivity of the system and hence the conditions of access and use of technological knowledge that cannot be fully appropriated by its inventors. It enables to appreciate the systemic conditions that shape the actual costs of knowledge. In this context it is clear that the quality of knowledge governance mechanisms at work within the economic system and the consequent levels of knowledge connectivity of the system are crucial to preserve the persistence of the growth process.

The identification of these constraints paves the way to stress the role of policy interventions finalized to keep the system in motion on the growth path and to avoid to falling into the trap of equilibrium. Effective knowledge governance enables systems to accumulate at faster rates the flows of new knowledge into the stock of public knowledge and to reduce the costs of accessing and using it.

The new knowledge-intensive technologies account not only for the growth of output and total factor productivity but also for the further accumulation of technological knowledge that in turn feeds the reduction of its cost. This dynamics seems able to account for the shift of advanced economies, away from the manufacturing industry typically characterized by a strong capital intensity to knowledge economies characterized by the large output elasticity of knowledge and a strong knowledge intensity. In an open economy framework of analysis this dynamics is reinforced by the competitive advantage stemming from the relative size of the knowledge stock that strengthens their specialization in the generation and use of technological knowledge as both an output and input.

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