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KNOWLEDGE PROPERTIES AND ECONOMIC POLICY: A NEW LOOK

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KNOWLEDGE PROPERTIES AND ECONOMIC POLICY: A NEW LOOK[1]

FORTHCOMING IN SCIENCE AND PUBLIC POLICY

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ABSTRACT. This paper explores the full range of effects of knowledge properties and explains how knowledge properties such as transient appropriability, non-exhaustibility and indivisibility do not only have negative effects, but also positive ones. Knowledge externalities help reduce the cost of knowledge and imitation externalities reduce the revenue and profitability of innovations. Their effects need to be considered jointly in a single analytical framework. An analysis of their combined effects questions the scope of application of the "Arrovian postulate" according to which the limited appropriability of knowledge due to its uncontrolled dissemination reduces invention. This ignores spillovers of outside knowledge, which increase invention. These are the two opposing faces of the limited appropriability of knowledge. Policy implications suggest that along with public interventions designed to support the supply of knowledge and to compensate for missing incentives, much attention should be paid to all interventions that favour the dissemination of knowledge and the knowledge connectivity of the system.

Keywords: Knowledge Properties; Knowledge Spillovers; Technology Production Function; Knowledge Production Function; Appropriability trade-off.
JEL classification: O33

1. INTRODUCTION

The aim of the paper is to explore the full range of consequences of the knowledge properties first identified by Kenneth Arrow (1962) and elaborate a more comprehensive framework for economic policy. The pathbreaking analysis of knowledge as an economic good enables Arrow to identify the idiosyncratic properties of knowledge compared with standard goods. Knowledge is characterized by low levels of appropriability, limited exhaustibility and substantial indivisibility. These knowledge properties have always been regarded as problematic and the cause of substantial market failure with major implications for public policy. A better appreciation of the implications of knowledge properties calls for a more balanced

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view of the full range of their effects and hence a more articulated set of economic policies (Antonelli and David, 2016).

The rest of the paper is structured as follows. Section 2 presents new advances in the economics of knowledge: the technology production and knowledge generation functions, transient knowledge appropriability, diachronic and pecuniary knowledge externalities. Section 3 presents a graphic analysis of the basic intuition, further implemented by a simple Schumpeterian (quality ladders) model that enables the full set of effects of the Arrovian properties of knowledge to be singled out: not only the depreciation of knowledge and its selective undersupply with the well-known implications in terms of market failure, but also a reduction in knowledge costs and its additional supply driven by the positive effects of knowledge externalities. The conclusions discuss the implications for policy analysis.

2. FROM SPILLOVERS TO KNOWLEDGE EXTERNALITIES

The early economics of knowledge focused attention on the theoretical analysis of technological knowledge as an economic good identifying its limited appropriability, non-excludability, non-rivalry in use and intrinsic information asymmetries (Arrow, 1962 and 1969). A large amount of the literature has dwelled on the issue and elaborated the notion of knowledge market failure. According to this approach, the intrinsic limits to the appropriability of knowledge reduce the incentives to generate it and lead to undersupply. Systematic public interventions would be necessary to support the generation of knowledge by means of either subsidies or its direct generation with the creation of a large public research system (David, 1993; Antonelli, 2009).

The discovery by Zvi Griliches (1979, 1984, 1992) of the positive aspects of limited appropriability in terms of knowledge spillover had a major impact. In a first step, the intuition of Zvi Griliches in fact enabled – by means of the technology production function where knowledge enters the production function as a fundamental input along with capital and labour – the positive effects of knowledge spilling from third parties on the actual production costs of every other agent in the system to be appreciated. This approach provided rich empirical evidence that confirmed the positive role of spillovers and knowledge externalities in assessing total factor productivity growth (Hall, Mairesse, Mohnen, 2010).

Much attention has been paid to exploring the characteristics of spillovers. Three significant distinctions have been made: i) imitation externalities vs knowledge externalities; ii) pure vs pecuniary externalities; iii) synchronic vs diachronic externalities.

Let us consider them in turn. Imitation externalities take place when the first Arrovian property of knowledge, its well-known limited appropriability, and the consequent uncontrolled leakage of proprietary knowledge enable imitators to 'steal' innovations from 'inventors', enter the market, reduce the price of the product and shrink innovators' profits. Imitation externalities take place in the same product markets where 'inventors' introduced the innovation (Bloom, Schankerman and Van Reenen, 2013; Aghion, Akcigit and Howitt, 2015). Imitation externalities are mainly, if not exclusively, negative, at least for inventors. At the system level they engender a zero sum game: the losses of inventors equal the advantages of rivals. Knowledge externalities, on the other hand, take place when the knowledge inputs that have made the innovation possible are accessed and re-used as intermediary inputs for the generation of new technological knowledge. Knowledge externalities apply in a wide range of industries and are not bound to the sector and product market of introduction because of the powerful effects of inter-industrial knowledge flows (Scherer, 1982). The effects of knowledge externalities are mainly positive as they stem from the generalized access to proprietary knowledge and its secondary use as an input at low costs. Knowledge externalities enable the positive effects that stem from the Arrovian properties of knowledge –including limited exhaustibility and non divisibility- to be taken full advantage (Griliches, 1979, 1984, 1992).

Pure (technical) externalities take place when spillovers can be accessed and used at no cost. Pecuniary externalities apply when, on the other hand, the use of and access to spillovers require dedicated resources and specific absorption costs. This interpretation of the notion of pecuniary externalities extends the original where it deals with price effects on the recipient's side and not with costs incurred by the customers. This extension applies to knowledge spillovers as it enables to include the costs incurred by the recipients to benefit from the spillovers. Technological knowledge spills freely in the atmosphere but the acquisition and use of knowledge spillovers are far from free: their access and use require dedicated activities to absorb the necessary external knowledge (Cohen and Levinthal, 1989 and 1990). Antonelli (2009) suggests that knowledge externalities are pecuniary rather than pure. The higher the absorption costs are and the lower the pecuniary knowledge externalities, the lower the positive effects of the amount of knowledge available. This in turn implies that low absorption costs of external knowledge enable a reduction in knowledge cost as an input in the technology production function of all the other goods, and most importantly, in the knowledge generation function of new technological knowledge.

The initial understanding of knowledge externalities as pure and synchronic has been eventually replaced by seeing them as pecuniary and diachronic. The distinction between synchronic and diachronic knowledge externalities is relevant in this context. According to the first specifications of Griliches – further elaborated by Romer (1990 and 1994) – knowledge externalities stem from the spillover of the non-appropriable component of the knowledge generated by each firm. As such, knowledge externalities are implicitly synchronic. As a matter of fact, the distinction between the appropriable and the non-appropriable components of knowledge remains unclear. Griliches (1979 and 1992) provided the methodology to measure their effects, but did not venture into any ex-ante distinction. Romer (1990 and 1994) did, with unclear results.

The notion of diachronic knowledge externalities enables this ambiguity to be overcome. All newly generated knowledge can be appropriated, but only for a limited stretch of time. Eventually, in fact, all knowledge becomes public. The distinction between appropriable and non-appropriable components disappears. The two effects do take place, but in a sequence. Mansfield (1985) using survey data, finds that knowledge of a research project is in the hands of competitors within roughly 18 months. Adams and Clemmons (2013) calibrates diffusion lags among fields and sectors for science, finding that the mean lag is about six years in standard data.

According to Antonelli (2017), knowledge externalities should be regarded as diachronic and the appropriability of knowledge transient rather than partial. All knowledge generated at each point in time can be appropriated by 'inventors'. The windows of appropriation, however, are short. Eventually all knowledge becomes public. Knowledge externalities stem from the summation of all the flows of knowledge, generated at each point in time, but with a lag determined by the windows of appropriation. The notion of diachronic knowledge externalities enables the problematic distinction between appropriable and non-appropriable components of knowledge and the related problems regarding the incentives to actually fund R&D activities to be overcome.

At each point in time there is a large stock of public knowledge and a 'small' stock of private knowledge. The former is the result of the spillover of proprietary knowledge and the latter is the result of the short-term appropriation of proprietary knowledge by its producers. The laws of accumulation of the stock of public knowledge play a central role. The higher the levels of knowledge connectivity of a system are, then the more effective the actual accumulation of the stock of public knowledge is.

The flows of proprietary knowledge eventually but inevitably become public and add to the stock. Inventors can retain the benefits of their proprietary knowledge only for a limited stretch of time.

Equation (1) specifies the laws of accumulation of the stock of public knowledge (SPT) as a function of the summation of the yearly flows of new knowledge (A_t) after accounting for the lag in knowledge availability (l) and assuming that the current period were t_1 and the initial year t_0 and the most recent flow of knowledge lags the current year by l years, and taking into account depreciation/obsolescence (d), as it follows:

$$S_{t_1} = \sum_{t=t_0}^{t_1-\ell} (1-d)^{t_1-\ell-t} A_t$$

(1)

The quality of the accumulation process matters. The effective accumulation of a well-structured and organized stock of public knowledge is not obvious. It depends on the levels of knowledge connectivity of the system in which each firm is embedded. If connectivity is higher and accumulation is faster and more effective, then access to the stock of external knowledge will be less expensive. Consequently, the better are the knowledge governance mechanisms that implement the knowledge connectivity of the system and the larger the size of the stock of public knowledge, the lower the costs to access and use it.

The effects of pecuniary and diachronic knowledge externalities can be explored by means of the knowledge generation process where external knowledge spilling from third parties favours the generation of new knowledge. The new economics of knowledge has in fact progressively shifted analysis away from the properties of knowledge as an economic good to the characteristics of the knowledge generation process as a dedicated economic activity aimed at its generation. A study of the knowledge generation process has shown that, together with current expenses in R&D activities, the stock of knowledge, both internal and external to each agent, plays a strong role as an indispensable and complementary input. According to the latest advances in the economics of knowledge, new technological knowledge is generated by means of a recombination of the existing technological knowledge (Weitzman, 1996). It becomes increasingly clear that the lower the costs of accessing and using the existing stock of knowledge are, then the greater the amount of external knowledge that each agent can access at low absorption costs and the more cost-effective the knowledge generation process.

The growing empirical evidence provided by the economics of knowledge confirms that the generation of new technological knowledge consists in the recombination of existing modules of knowledge and is characterized by complementarity between internal research activities and external knowledge. Jaffe (1986) first estimated a knowledge generation function that takes knowledge externalities into account. Arora and Gambardella (1990 and 1994) show that technological knowledge, external to each firm, is an indispensable input for the generation of new technological knowledge. Veugelers (2006) confirms the role of external knowledge and the related sourcing activities required to identify, access and use it in the generation of new technological knowledge. Lööf and Johanson (2014) articulate and implement the analysis of the complementarity between internal and external knowledge showing that internal research activities are essential to accessing and using external knowledge in the same way that access to external knowledge is indispensable when performing effective R&D activities intramuros. Antonelli and Colombelli (2015) show that the knowledge generation function displays the typical traits of an O-ring technology in which no input or stock of internal knowledge or stock of external knowledge can fall to zero levels. Antonelli, Krafft and Quatraro (2010) show the relevance not only of the size but also of the composition of the knowledge stock available in a context – in terms of coherence and complementarity – in supporting the generation of new technological knowledge.

The properties of the system in which firms are embedded play a crucial role in assessing the actual access and use conditions of the stock of public knowledge. The quality of knowledge governance of an economic system improves actual access to the stock of knowledge and reduces its absorption costs without endangering the incentives to generate it. Large absorption costs of existing knowledge, in fact, are likely to reduce the positive effects of the dynamics of the stock of knowledge. The higher the connectivity of the system, then the lower knowledge absorption costs are. Knowledge connectivity, in turn, is determined by knowledge governance: the set of rules, procedures, modes and protocols that organize the generation, dissemination and use of knowledge in an economic system as a collective process. This includes the conditions that make possible the actual use of the scientific knowledge supplied by the State for economic purposes through its direct support to the academic system and the intellectual property right regime (Antonelli and Link, 2015).

When and where the quality of the knowledge governance and connectivity of the system is rich and access to existing technological knowledge can be done at low cost, new technological knowledge can be generated at costs that are below equilibrium levels: its costs are below the levels that they would have been at, without spillovers. The supply curve of technological knowledge shifts downwards and identifies an equilibrium supply of technological knowledge that can be even larger than in the case of technological knowledge with quasi-perfect appropriability conditions. In such an extreme case, the Arrovian postulate needs to be reconsidered: there is no need for public intervention to support the supply of additional technological knowledge in order to compensate for the market failure engendered by the alleged missing incentives caused by the limited appropriability of knowledge.

When, on the other hand, the quality of knowledge governance and the connectivity of the system is poor, the cost of access to the stock of existing knowledge is high and not even the positive quantitative effects of the increasing size of the stock of public knowledge take place. Intellectual property regimes characterized by strong exclusivity and long duration may actually impede access to the existing stock of knowledge. When the quality of the knowledge governance is poor and the institutional set-up of the system is weak, access to external knowledge is too expensive to compensate for its transient appropriability.

These advances of the economics of knowledge need to be integrated in a single framework so as to better appreciate the full range of their economic effects.

3. THE ANALYSIS

The basic intuition presented so far is elaborated in two steps. The graphic exposition introduces the ideas. The model frames it in the context of the Schumpeterian growth theory.

3.1 A GRAPHIC EXPOSITION

Let us now explore the consequences of the framework with a simple graphic exposition of the market for knowledge. The graphical analysis impinges upon the analysis of the effects of the limited appropriability on knowledge on both its costs and its derived demand, i.e. on the demand of knowledge as an intermediary input in the technology production function (Antonelli, 2017). Figure 1 presents on the vertical axis the return of research projects (RP) and their costs (u) and, on the horizontal axis, the quantity of knowledge (A). The position of derived demand curve of knowledge (D_1) is determined by its marginal product in value. Its supply curve (S_1) is analyzed as the standard horizontal summation of the marginal costs of knowledge as defined by a knowledge generation function. In standard market conditions that would apply if knowledge were a 'standard' good, supply and demand find an equilibrium in point E that identifies the equilibrium quantities T_E and the price of knowledge u_1. This benchmark is confronted with the market conditions that take place when the "Arrovian" properties of knowledge are considered.

Figure 1 explores the full range of effects of knowledge properties:

i) because of the well-known negative effects of the transient appropriability of knowledge on the price of goods produced using knowledge as an input, the derived demand of knowledge as a standard good D_1 shifts to the derived demand of knowledge as a good characterized by transient appropriability D_2. Due to well-known transient knowledge appropriability and the consequent negative effects of imitation externalities, in fact, the price of the final goods produced using knowledge as an input – after a short time window – falls below the levels of the benchmark case of a standard economic good because of the entry of imitators that do not bear the costs of knowledge. Consequently, the demand for technological knowledge shifts downwards, below the benchmark levels of a standard good. The intercept of the actual derived demand for technological knowledge – characterized by the Arrovian properties – is consequently lower than the benchmark derived demand of technological knowledge if it were a standard good and;

ii) because of the positive effects of knowledge non-exhaustibility, cumulability and complementarity, the supply of knowledge as a standard good S_1 shifts to S_2. We assume in fact that the stock of all the existing knowledge generated and cumulated until that time is a complementary, indispensable input for the generation of new technological knowledge. Its use is not free: it can take place at a specific cost that accounts for a wide range of activities that are needed to absorb and use it. Due to the positive effects of knowledge externalities, the larger the size of the stock of public knowledge, then the better the knowledge governance mechanisms are and the lower the cost of knowledge as an intermediary input, itself an output of the knowledge generation activities. Consequently, the larger the stock of quasi-public knowledge is, then the lower the knowledge supply schedule in the markets for knowledge.

The literature has very much emphasized the first case i.e. the shift in the derived demand of knowledge, but it has paid little attention to the second case i.e. the shift of the supply curve. The latter takes place when the cost of accessing external knowledge and using it as an input for the generation of new knowledge is low and does not take place when, on the contrary, it is high.

Let us analyse them in turn. When the system is not able to support the generation of knowledge of the agents with appropriate levels of pecuniary knowledge externalities, and the stock of knowledge available in the system is low, the supply curve of knowledge as a standard good and the supply curve of knowledge as an Arrovian good coincide in S_1 which, in equilibrium, defines a large u: the standard knowledge market failure applies. External knowledge is indispensable, but its use cannot exert any positive effect on u. Transient knowledge appropriability displays all the negative effects of imitation externalities on the knowledge demand curve with no positive effects on the long-term knowledge supply curve in terms of knowledge externalities. Figure 1 shows the typical situation of undersupply that is determined by the backward shift of the knowledge demand curve with a given supply curve and the consequent shift of the equilibrium quantity of knowledge produced from T_E to T_A. The "Arrow-equilibrium" quantity is lower

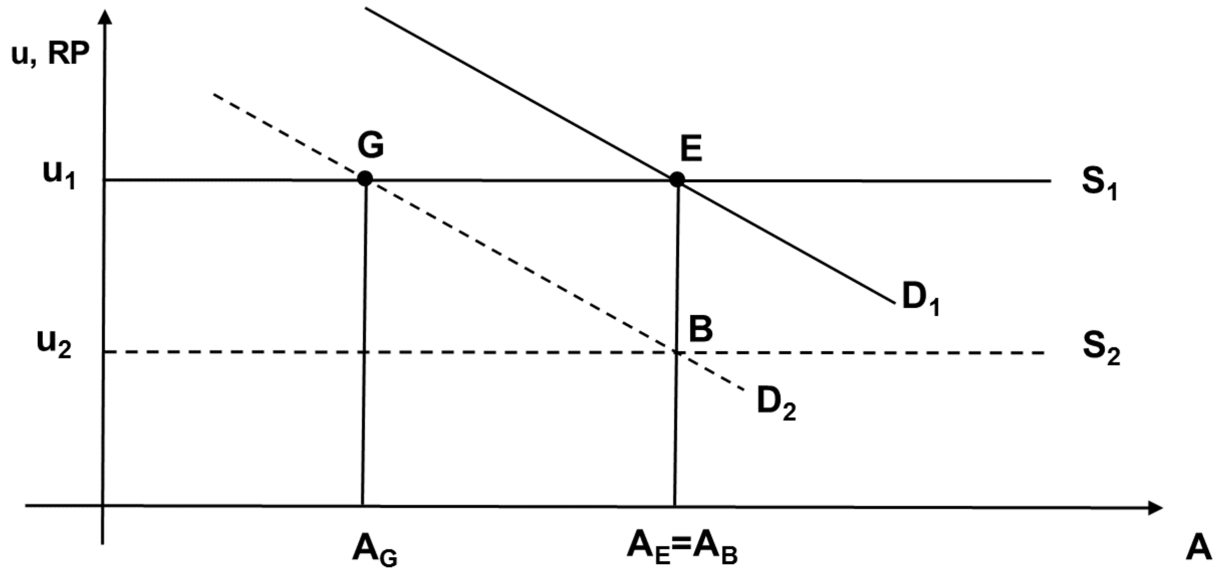
This effect is the basic reference for much work on the notion of knowledge market failure and the consequent knowledge undersupply that has provided the rationale for a public policy aimed at supporting an increase in the generation of additional knowledge through direct supply by the State with the funding of public research centres and universities, the provision of public subsidies to firms funding R&D activities, and public procurement.

When the stock of knowledge available in the system is large and knowledge governance mechanisms are effective, diachronic pecuniary knowledge externalities are relevant. Transient appropriability displays both positive and negative effects where the former can compensate for the latter. The cost of knowledge as an output (u) is below equilibrium levels. In this case, the notion of market failure needs substantial reconsideration.

With large spillovers complemented by good knowledge governance protocols and a large size of the stock of public knowledge available within the system, the generation of technological knowledge can rely on access to external knowledge at low absorption costs. In the recombinant knowledge generation process, firms can take advantage of the low levels of v so as to substitute R&D activities with the use of 'cheap' existing external knowledge. The general costs of knowledge decline with the downward shift of the long term knowledge supply curve from S_1 to S_2. Now, in the system, the amount of knowledge generated can match the equilibrium conditions so that $A_E = A_B$. The standard hypothesis about undersupply no longer applies. Moreover, the cost of technological knowledge is lower than in equilibrium. As Figure 1 clearly shows, $u_1 > u_2$.

In the extreme case, shown by Figure 1, the recombinant generation of technological knowledge that takes place in a system – endowed with a large stock of public knowledge and able to support it with high quality knowledge governance – where it can take advantage of major pecuniary knowledge externalities, even after taking into account the downward shift in the demand of knowledge engendered by transient appropriability, leads to a "Griliches-equilibrium" supply of technological knowledge that is actually as high as expected in the "Arrow-equilibrium" and yet cheaper[2].

Figure 1. From knowledge market failure to pecuniary knowledge externalities



Let us now summarize the analysis. When only the effects of the transient appropriability of knowledge on the derived demand of knowledge are accounted for and the effects on the supply curve are not considered or are not empirically relevant, as in the standard knowledge market failure approach, the demand schedule for knowledge exhibits a downward shift from D_1 to D_2. The "Arrow-equilibrium" is found in A where the quantity of knowledge $A_A < A_E$.

When and if, however, the 'positive' effects of transient knowledge appropriability on both the supply and the demand curve are taken into account, but the institutional set-up of the system endowed with a large stock of knowledge is able to provide

[2] It is even possible to consider the possibility that the positive effects of spillovers do overcome the negative effects of imitation.

substantial diachronic pecuniary knowledge externalities, the cost of external knowledge – a necessary and complementary input for the generation of new technological knowledge – falls to such levels that the supply of knowledge exhibits a downward shift from S_1 to S_2 so as to identify, even with a knowledge demand schedule that reflects – with the downward shift from D_1 to D_2 – the negative effects of the transient appropriability of knowledge, the "Griliches-equilibrium" point B where there is no knowledge undersupply and the actual price of knowledge u_2 is lower than the standard price of knowledge u_1. When and if the institutional set-up of the system and the size of its knowledge stock is able to support the generation of new technological knowledge with large pecuniary knowledge externalities, the amount of technological knowledge that the system is able to generate is as large as if knowledge were a standard good and its costs are actually lower[3].

In terms of quantity, there is no market failure and no knowledge undersupply when and if the quality of the knowledge governance and knowledge connectivity of the system are so high that the levels of the cost of external knowledge v and hence the cost of knowledge u are reduced to the minimum levels of u_2. In the range of conditions comprised between the two extremes u_1 and u_2 some knowledge market failure with the consequent under-supply takes place. Although firms can access external knowledge at costs that are lower than those of internal research activities, the "Griliches-equilibrium" amount of knowledge generated by the system is below the equilibrium levels for standard goods. In these cases, the downward shift of the supply curve is not able to compensate for the downward shift of the demand curve.

There is a time element that has not been included in the analysis so far. The timing of the leakage and access to external knowledge may differ. The leaking out in the public domain of one's own knowledge can occur faster than the appropriation of the knowledge of others. If this is the case, it could well be that a selection effect occurs in the short run that could have been prevented if access to outside knowledge had occurred faster. The Arrovian postulate would apply. On the contrary, however, it seems appropriate to consider the case with timing of the leakage that is much larger than the absorption lag. In this case, innovators can retain their competitive advantage by building on the knowledge generated by third parties that is rapidly absorbed. The Arrovian postulate would not apply.

The effects of knowledge indivisibility and non-exhaustibility augment the cases considered so far with major dynamic implications. For given levels of knowledge governance, it is clear that the larger the stock of public knowledge, the lower the cost of external knowledge, hence the lower the costs of knowledge as an output (u). With time, the stock of public knowledge keeps increasing and consequently both the

[3]Note that Figure 1 assumes a flat supply curve. A positive slope would make the argument even stronger. The actual slope and position of the curves are – of course – an empirical matter.

costs of external knowledge and the cost of knowledge as an output (u) decline. This leads to the increase in the generation of the flow of knowledge generated at each point in time. The inter-temporal dynamics of knowledge costs is clearly characterized by a negative slope. As a consequence, the stock of public knowledge increases at faster rates. The dynamics is clearly self-reinforcing. At each point in time, countries with a larger stock of public knowledge enjoy not only lower levels of knowledge costs than countries with a small knowledge stock, but also faster rates of generation of new knowledge and faster rates of accumulation of the stock of knowledge. For a given small initial difference, the gap is deemed to increase over time. The dynamics of the process display typical non-ergodic characters that may be self-reinforcing and fuel an increase in asymmetries unless a decline on the quality of knowledge governance mechanisms slows downs the process.

The structure of knowledge interactions and transactions among agents within the business sector and between the business sector and the public research system becomes the central issue. Good knowledge governance mechanisms are able to improve the knowledge connectivity of the system and hence access conditions to existing knowledge. Countries with large knowledge stocks and good knowledge governance able to implement good knowledge connectivity protocols can enjoy not only a large supply of technological knowledge, but also low technological knowledge costs and hence a competitive advantage. Countries endowed with a smaller stock of knowledge and less able to command the good knowledge governance practices that are needed to implement high powered knowledge connectivity protocols suffer the negative effects of the Arrovian market failure, the undersupply of knowledge and a clear competitive disadvantage compared with countries where the absorption costs of the stock of existing knowledge are lower. The gap between countries increases over time because of the effects of the accumulation of larger flows of knowledge in countries with a larger stock.

A reduction in the cost of knowledge below the benchmark levels that would take place, were knowledge a standard economic good, has major economic implications: the fall in the price of knowledge below equilibrium levels accounts for total factor productivity levels and supports the introduction of innovations in the Schumpeterian framework of the creative response to out-of-equilibrium conditions.

3.2. THE MODEL

This section presents a simple model along the lines of the Schumpeterian growth theory. Since Griliches' time economists have emphasized the division of labor between competitive final goods producers and monopoly producers of intermediate goods: innovation occurs in the latter sector. In the Schumpeterian (Quality Ladders) framework, competitive final goods producers employ a range of intermediates across different lines. As the quality of these goods rises, overall productivity in the final goods sector improves. Hence technology is external to the final goods sector and appears as productivity gains in that sector, rather than the intermediate goods sector where innovation takes place. Each producer of an intermediate good is a monopolist until a still higher quality or productivity does not leapfrog their level of quality or productivity. This framework provides equilibrium conditions for firms in each sector, including for R&D in the intermediate goods sector. The setup appears below:

$$(2)\ \ Y_t = (L/N)^{1-\alpha} \int_0^N A_{it}^{1-\alpha}\, x_{it}^{\alpha} di$$

This is the final goods production function; the term before the integral in (2) is labor per intermediate, □/□, in which □ is labor, and □ is the measure of the intermediates. In equilibrium, the integral, which is taken over the continuum of intermediates, generates aggregate productivity; □□□ is the amount of intermediate of type i; and □□□ is productivity. Final goods are the numeraire and the price of □□ is unity. Intermediate goods producers set the price □□□ of each intermediate □□□ (which is treated as perishable and lasting one period) equal to its value marginal product in the final goods sector. Therefore:

$$(3)\ \ p_{it} = \frac{\partial Y_t}{\partial x_{it}} = \alpha (L/N)^{1-\alpha} A_{it}^{1-\alpha} x_{it}^{\alpha-1}$$

Since each unit of the intermediate (for simplicity) is assumed to be produced one-for-one from the final good, the profit of the monopoly producer Π . . is the price of the intermediate times its quantity minus a price of unity (the numeraire price) times quantity. Hence:

$$(4)\ \ \Pi_{it} = \alpha (L/N)^{1-\alpha} A_{it}^{1-\alpha} x_{it}^{\alpha} - x_{it}$$

Intermediate goods producers, who are monopolists, choose • . .to maximize Π . .:

$$(5)\ \ \frac{d\Pi_{it}}{dx_{it}} = \alpha^2 (L/N)^{1-\alpha} A_{it}^{1-\alpha} x_{it}^{\alpha-1} - 1 = 0$$

Solving (5) for the quantity of the intermediate yields:

$$(6)\ \ x_{it}^{*} = \alpha^{\frac{2}{1-\alpha}} \left(\frac{L}{N}\right) A_{it}$$

To find the equilibrium reduced form of the aggregate production function, substitute (6) into (2):

$$(7)\ \ Y_t = \left(\frac{L}{N}\right)^{1-\alpha} \int_0^N A_{it}^{1-\alpha} \left[\alpha^{\frac{2}{1-\alpha}} \left(\frac{L}{N}\right) A_{it}\right]^{\alpha} di = \alpha^{\frac{2\alpha}{1-\alpha}} \left(\frac{L}{N}\right) \int_0^N A_{it} di = \alpha^{\frac{2\alpha}{1-\alpha}} \left(\frac{L}{N}\right) A_t$$

This shows that the overall level of productivity/technology increases output of final goods one-for-one.

Next, use (6) to find the maximum value of profits from an intermediate good. This will be used to specify the returns to investment in research and development.

Substitution of (6) into (4) yields:

$$(8)\quad \Pi_{it}^{*} = \pi(L/N)A_{it}$$

In (8), $\pi = (1-\alpha)\alpha^{\frac{1+\alpha}{1-\alpha}}$.

Equation (8) is the instantaneous value of a new intermediate once it is invented. To determine the value of investment in R&D, assume for simplicity that invention of a better intermediate good takes place after □ periods (a more general approach lets the period of the intermediate follow an exponential distribution). The current intermediate is at that time replaced by a higher quality intermediate. Here, □ > 0 is an inverse indicator of the speed of replacement or obsolescence, and it is a direct measure of the ability to appropriate returns from invention. The value of an innovation, assuming a one period lag between invention and implementation, is:

$$(9)\quad V_{it} = \sum_{\tau=t+1}^{n} \frac{1}{(1+r)^{\tau-t}} \pi \cdot (L/N) \cdot A_{it} = \frac{1}{r}\left(1 - \frac{1}{(1+r)^{n}}\right) \cdot \pi \cdot (L/N) \cdot A_{it}$$

In this equation, □ is the interest rate. As □ falls/rises, □□□ falls/rises, as previously mentioned. To complete the specification of returns to invention, let the probability of discovery be:

$$(10)\quad \phi = \eta \cdot (R_{it}/A_{it})^{\theta} \cdot S_t^{\sigma}\ ,$$

In (10) the exponents are elasticities of the probability with respect to each input on the right. Here, □□□/□□□ is R&D effort (internal knowledge) normalized by productivity, indicating that more advanced goods have higher R&D costs; and □□ is the exogenous stock of public knowledge. The expected benefit from R&D is □ · □□ . Subtracting the cost of R&D from the net benefit, the expected net benefit from R&D is:

$$(11)\quad E_R = \phi \cdot V_{it} - R_{it}$$

where E_R is the expected net benefit from R&D.

Now take the derivative of (11) with respect to R&D using (9) and (10) and set this equal to zero. The result is:

$$(12)\ R_{it}^{*} = A_{it} \cdot S_{t}^{\frac{\sigma}{1-\theta}} \cdot \left[\theta \cdot \eta \cdot \frac{1}{r}\left(1-\frac{1}{(1+r)^{\pi}}\right) \cdot \pi \cdot (L/N)\right]^{\frac{1}{1-\theta}}$$

Clearly, equilibrium R&D, a measure of the demand for knowledge, increases with the stock of public knowledge but decreases when □ decreases. The stock of public knowledge increases research but a decline in the period of appropriation of the returns decreases research.

Note that we could extend (12) to include separate prices for inside research and outside public knowledge and deliberate acquisition of the latter:

$$(13)\ E_A = \phi \cdot V_{it} - p_R \cdot R_{it} - p_S \cdot S_{it}$$

where E_A is the expected net benefit from knowledge.

We can then maximize (13) over both variables on the assumption that the net benefit is concave.

4. CONCLUSIONS AND POLICY IMPLICATIONS

This paper has integrated recent advances in the economics of knowledge concerning knowledge properties, ranging from the limited (transient) appropriability of knowledge to its indivisibility and non-exhaustibility, in order to implement an analysis of the full range of effects by applying the new tools of the economics of knowledge, the knowledge generation function combined with the technology production function. It has applied this analytical framework to understand the effects on the technological knowledge markets of both a reduction in the derived demand of knowledge as an input in the technology production function and a reduction in the cost of technological knowledge in the knowledge generation function. It has identified a reduction in the price of knowledge as a key issue for its positive effects on the supply of knowledge.

The implications of the analysis carried on so far are very important. Too much attention has been paid to the presumed generic undersupply of knowledge stemming from knowledge market failure. Too much effort has also been made to compensating for the presumed generic undersupply with public interventions aimed at increasing all kinds of research efforts with the provision of indiscriminate subsidies to firms performing any kind of R&D activities and most importantly, the direct supply of scientific and technological knowledge with the creation of a large public research system, including the academic system, deprived of any strategy.

This generic approach applies only when the positive effects of knowledge externalities on the costs of external knowledge cannot compensate for the negative effects of transient appropriability on its use as an input in the production of all the other goods.

Public policy should focus on the laws of accumulation of the stock of public knowledge. A reduction in the cost of technological knowledge stems from an effective accumulation of the stock of public knowledge. The accumulation of an effective stock of public knowledge is not obvious and automatic. Knowledge items can remain dispersed and fragmentary across the system engendering large screening and absorption costs. The levels of knowledge connectivity of the system play a major role in enforcing the accumulation of a well-structured and effective stock of public knowledge. The larger the levels of diachronic and pecuniary knowledge externalities are, the greater the chance of generating new knowledge items and hence, with a given research cost, the lower the unit costs of new technological knowledge and the larger the actual amount of knowledge generated.

In a system characterized by high levels of knowledge connectivity and high levels of knowledge governance, there is little risk of generic knowledge market failures and systematic undersupply of the quantity of knowledge, as predicted by the Arrovian approach. The institutional characteristics of the systems that are able to support the creative reaction of firms play a crucial role in this context since they affect the user costs of the stock of public knowledge. Here, the famous quotation of Thomas Jefferson seems most appropriate: "he who receives an idea from me, receives instruction himself without lessening mine; as he who lights his taper at mine, receives light without darkening me. That ideas should freely spread from one to another over the globe, for the moral and mutual instruction of man, and improvement of his condition, seems to have been peculiarly and benevolently designed by nature, when she made them, like fire, expansible over all space, without lessening their density in any point, and like the air in which we breathe, move, and have our physical being, incapable of confinement or exclusive appropriation." Along these metaphoric lines, the quality of the institutional set of an economic system from the viewpoint of the most effective use of technological knowledge seems to consist in the architectural design of the distribution of mirrors that is able to maximize the amount of light produced by each candle.

The reduction of the exclusivity of intellectual property rights and, more specifically, the extension of the trademark regime to patents with the implementation of compulsory licensing with royalties can play a major role in increasing the effective accumulation of the stock of public knowledge and favouring actual access to the existing stock of knowledge, without harming the role of patents as an indispensable factor in the dissemination of information on existing knowledge (Antonelli, 2007 and 2013).

An economic system that is able to increase and make the repeated use of technological knowledge to generate new technological knowledge easier, as well as all the other goods with governance mechanisms such as open innovation systems (see FLOSS: Free/Libre and Open Source Software) is likely to increase the positive effects of knowledge complementarity on the costs of knowledge as an input.

There is scattered evidence that effective dissemination policies are already in place. For example, Japan requires a period of public disclosure in which patent applications can be challenged as to their novelty, causing an increase in spillovers (and acceleration of imitation). The United States explicitly funds parts of its universities for working directly with companies.

A more systematic and comprehensive set of public interventions should be directed towards improving the dissemination of existing technological knowledge by favouring interactions between knowledge users and producers. Interactions between the public research system with special attention paid to the academic system, and firms should be the object of dedicated interventions. By the same token, user-producer interactions among firms should also be enhanced. The mobility of skilled personnel, with a focus on inventors, among firms and between firms and the public research systems -an effective tool to increase knowledge interactions- should be supported by dedicated policy interventions. Although knowledge externalities have a strong local character, international flows of technological knowledge can be strengthened with public actions that link the imports of knowledge-intensive products to enhanced user-producer interactions with a strong local content (Montobbio and Kataishi, 2015).

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