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THE ECONOMICS OF TECHNOLOGICAL CONGRUENCE

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THE ECONOMICS OF TECHNOLOGICAL CONGRUENCE[1]

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ABSTRACT. Technological congruence is defined by the matching between the relative size of outputs' elasticity with the relative abundance and cost of inputs in local factor markets. With given total costs, output is larger the larger is the output elasticity of the cheapest input. Technological congruence is a powerful tool that helps grasping many controversial aspects of growth accounting, international division of labor and specialization, technological and structural change. For years, it had received little attention because of the wide consensus that technological change was exogenous and neutral. But also subsequently, notwithstanding the developments made in the endogenous growth modeling, little attempt was made to provide a more advanced understanding of technological congruence. Its appreciation stems directly from the advances of the economics of innovation and its recent developments in understanding the endogenous determinants of the introduction and diffusion of directed technological changes. The levels of technological congruence are most relevant to influence the actual efficiency and to shape the competitive advance of firms and countries.

JEL Classification: O11, O30.
KEY WORDS: Factor shares, Technological change, Total factor productivity.

1. INTRODUCTION

Technological congruence is an important factor in economic growth both at the firm and the aggregate level. Technological congruence is defined by the matching of the relative size of outputs' elasticity to the relative abundance and price of production factors. More precisely, the congruence in terms of technology use implies that the choice of production inputs will be determined by the joint influence of the relative factor prices and their relative output elasticities.

Technological congruence has been little studied so far. Yet it is clear that output levels are strongly influenced by the levels of technological congruence. The output will be larger when the technology of the production process enables to use more intensively the production factors that are locally more abundant and hence cheaper. The factor intensity of the production process, in fact, is not determined only by the

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relative costs of inputs but also by the relative size of the output elasticity of each production factor. The distribution of outputs elasticity among inputs and the relative size of the output elasticity of each input, in turn, are key features of the economic representation of a technology (Antonelli, 2003 and 2012).

Technological congruence will be larger the larger the relative size of the output elasticity of the input with respect to its relative price in local factor markets. For a given budget, the output of a firm will be larger the larger is the output elasticity of the production factor that is locally cheaper. At the system level it is clear that the output will be larger the larger the output elasticity of the production factors that are locally more abundant and hence cheaper.

Technological congruence might be perceived in a specific historical context, yet is not static. Actually it is intrinsically dynamic, so that in each localized context relative changes of technological congruence will take place. Those changes depend on three sources of dynamics: a) the direction of technological change; b) the dynamics of factors costs; c) the combination of both. Let us consider them briefly in turn. For a given set of factor costs, the introduction of directed technological innovations that change the relative size of the output elasticity of the production factors will have powerful effects on the levels of outputs. The increase of the output elasticity of a given input will have positive effects if the input is locally most abundant and negative if –on the opposite- the output is locally the least abundant. On the other hand, for a given technological set, the changes in local factor markets will have positive effects if the price of the inputs that exhibit the largest output elasticity decrease, and –on the opposite- negative effects if they increase. Finally, the introduction of directed technological change and the dynamics of prices are very likely interdependent, so that it will be often the case that they will operate and determine technological congruence contemporaneously. It is clear that the levels of technological congruence are intrinsically dynamic as they depend on both the changes of the technologies and the local factor markets.

The notion of technological congruence, both in its static and dynamic aspects, has received, so far, little attention. The analysis of its determinants and effects has been quite poor with a scarce appreciation of its relevance. The identification of its implications, however, is calling growing attention (Zuleta, 2012). This substantial neglect can be considered a direct consequence of the widespread consensus about three strong economic assumptions: a) the stability and homogeneity of outputs elasticity; b) the static and exogenous character of factor endowments; c) the exogeneity and neutrality of technological change. Whereas major developments have been made to reconcile the last point, there is still tendency to adopt the first two.

The empirical evidence shows that these assumptions have many limitations. The output elasticity of inputs is far from stable at the aggregate level as it varies considerably across time and countries, as well as at the disaggregate level across firms, regions and industries (Krueger, 1999; Hall and Jones, 1999; Caselli and Coleman, 2006; Caselli and Feyer, 2004). The endowment of both tangible and especially intangible inputs cannot be any longer regarded as an exogenous and static character of economic systems. The relative abundance of many if not all production factors at each point in time can be considered the direct consequence of the economic activities that have been going on. Technological change cannot be any longer regarded as an exogenous process as it is widely recognized that economic forces play a central role in determining its characteristics including its direction that is far from being neutral (Acemoglu, 2003). A large literature has now explored in depth the strong role of economic factors in shaping the rates and direction of introduction and diffusion of technological changes (Antonelli, 2003).

As soon as these assumptions are questioned, the notion of technological congruence acquires a central role in economics. In the rest of the paper section 2 provides the analytical demonstration of technological congruence and section 3 outlines its implications for both economic analysis and policy.

2. THE EXISTENCE OF TECHNOLOGICAL CONGRUENCE

The standard Cobb-Douglas production function seems a suitable and effective starting point. The Cobb-Douglas specification, in fact, accommodates explicitly, with α and β, the output elasticities of the production factors and enables to analyze their changes. The standard Cobb-Douglas takes the following format:

$$\textbf{(1)}\ \ Y(t) = (K^{(\alpha)}\ L^{(\beta)})$$

where K denotes the amount of capital and L the amount of labor.

The cost equation is:

$$\textbf{(2)}\ C = rK + wL$$

Firms select the traditional equilibrium mix of inputs according to the slope of the isocosts given by ratio of labor costs (w) and capital rental costs (r) and the slope of isoquants. The equilibrium condition is:

$$\textbf{(3)}\ w/r = (\beta/\alpha)\ \ (K/L)$$

The substitution of the equilibrium condition into the production function, assuming that $\alpha+\beta=1$, leads to:

$$(4)\ Y = (w/r)^{\alpha}\ (\alpha/\beta)^{\alpha}\ L$$

To show the effect of α on the production function let us derive (4) with respect to α.

As D(f(x)g(x))=f'(x)g(x)+f(x)g'(x), by adopting f(x)= L (w/r)$^{\alpha}$ and g(x)= (α/β)$^{\alpha}$, we obtain:

$$\frac{dY(L)}{d\alpha} = L\left(\frac{w}{r}\right)^{\alpha}\left(\ln\frac{w}{r}\right)\left(\frac{\alpha}{\beta}\right)^{\alpha} + L\left(\frac{w}{r}\right)^{\alpha}\frac{d\left(\left(\alpha/\beta\right)^{\alpha}\right)}{d\alpha} \tag{5}$$

To get rid of d((α□β□$^{\alpha}$)/dα in (5), we derive it by applying the differentiation rule D((f(x)$^{g(x)}$)= f(x)$^{g(x)}$[g'(x)lnf(x)+g(x)f'(x)/f(x)] where f(x)= α□β and g(x)= α.

We thus obtain:

$$\frac{d\left(\left(\alpha/\beta\right)^{\alpha}\right)}{d\alpha} = \left(\frac{\alpha}{\beta}\right)^{\alpha}\left(\ln\frac{\alpha}{\beta} + \alpha\frac{1/\beta}{\alpha/\beta}\right) = \left(\frac{\alpha}{\beta}\right)^{\alpha}\left(\ln\frac{\alpha}{\beta} + 1\right). \tag{6}$$

By substituting (6) in (5), we obtain:

$$\begin{aligned}\frac{dY(L)}{d\alpha} &= L\left(\frac{w}{r}\right)^{\alpha}\left(\ln\frac{w}{r}\right)\left(\frac{\alpha}{\beta}\right)^{\alpha} + L\left(\frac{w}{r}\right)^{\alpha}\left(\frac{\alpha}{\beta}\right)^{\alpha}\left(\ln\frac{\alpha}{\beta} + 1\right) = \\ &= L\left(\frac{w}{r}\right)^{\alpha}\left(\frac{\alpha}{\beta}\right)^{\alpha}\left(\ln\frac{w}{r} + \ln\frac{\alpha}{\beta} + 1\right) = L\left(\frac{w}{r}\right)^{\alpha}\left(\frac{\alpha}{\beta}\right)^{\alpha}\left(\ln\frac{w}{r}\frac{\alpha}{\beta} + 1\right)\end{aligned}. \tag{7}$$

Since, by (4), Y(L) = L (w/r α/β)$^{\alpha}$, (7) can be reformulated as:

$$\frac{dY(L)}{d\alpha} = Y\left(1 + \ln\frac{w}{r}\frac{\alpha}{\beta}\right). \tag{8}$$

Equation (8) tells us that the output levels are clearly influenced by the relative size of the output elasticity of the two production factors. Specifically we see that output levels are larger the lower is r with respect to w and the larger is **α** with respect to **β.**

Let us now consider a more general case, with n factors. Each factor is denoted as F_i, with i={1..n}, and its elasticity to the output is ε_i. The level of production Y is given by a Cobb-Douglas function with constant returns to scale:

$$Y = \prod_{i=1}^{n} F_i^{\varepsilon_i}, \tag{9}$$

where $\Sigma_i\varepsilon_i=1$. Denoting with p_i the price of factor F_i and with p the output price, profits π are equal to:

$$\pi = pY - \sum_{i=1}^{n} p_i F_i, \tag{10}$$

from which $F_i = \frac{pY - \pi}{p_i} - \sum_{j\neq i}\frac{p_j}{p_i}F_j$.

From (9), we derive the marginal rate of technical substitution between F_i and F_j:

(11) $$\frac{\partial Y/\partial F_i}{\partial Y/\partial F_j} = \frac{\varepsilon_i F_i^{\varepsilon_i-1}\prod\limits_{k\neq i}^{n} F_k^{\varepsilon_k}}{\varepsilon_j F_j^{\varepsilon_j-1}\prod\limits_{k\neq j}^{n} F_k^{\varepsilon_k}} = \frac{\varepsilon_i F_i^{\varepsilon_i-1}}{\varepsilon_j F_j^{\varepsilon_j-1}}\frac{F_j^{\varepsilon_j}}{F_i^{\varepsilon_i}} = \frac{\varepsilon_i}{\varepsilon_j}\frac{F_j}{F_i}.$$

The equilibrium condition for the generic couple of factors F_i, F_j is obtained by imposing (11) equal to the ratio of the prices of factors:

(12) $$\frac{\partial Y/\partial F_i}{\partial Y/\partial F_j} = \frac{\varepsilon_i}{\varepsilon_j}\frac{F_j}{F_i} = \frac{p_i}{p_j}.$$

From (12), in equilibrium it must be:

(13) $$F_j = \frac{p_i}{p_j}\frac{\varepsilon_j}{\varepsilon_i}F_i \text{ for all i,j.}$$

By substituting (12) in (9), we obtain:

(14) $$Y(F_k) = \prod_{i=1}^{n} F_i^{\varepsilon_i} = F_1^{\varepsilon_1}\cdot\left(\frac{p_1}{p_2}\frac{\varepsilon_2}{\varepsilon_1}F_1\right)^{\varepsilon_2}\cdot\left(\frac{p_1}{p_3}\frac{\varepsilon_3}{\varepsilon_1}F_1\right)^{\varepsilon_3}\cdot\square\cdot\left(\frac{p_1}{p_n}\frac{\varepsilon_n}{\varepsilon_1}F_1\right)^{\varepsilon_n} = F_k\prod_{j\neq k}\left(\frac{p_k}{p_j}\frac{\varepsilon_j}{\varepsilon_k}\right)^{\varepsilon_j} =$$

$$= F_k\prod_{j\neq k,l}\left(\frac{p_k}{p_j}\frac{\varepsilon_j}{\varepsilon_k}\right)^{\varepsilon_j}\left(\frac{p_k}{p_l}\frac{\varepsilon_l}{\varepsilon_k}\right)^{\varepsilon_l} = F_k\prod_{j\neq k,l}\left(\frac{p_k}{p_j}\frac{\varepsilon_j}{\varepsilon_k}\right)^{\varepsilon_j}\left(\frac{p_k}{p_l}\right)^{\varepsilon_l}\left(\frac{\varepsilon_l}{\varepsilon_k}\right)^{\varepsilon_l}.$$

Let us differentiate (14) with respect to a generic ε_l, with $l\neq k$. As $D(f(x)g(x))=f'(x)g(x)+f(x)g'(x)$, by adopting $f(x)= F_k\, \Pi_{j\neq k,l}((\varepsilon_j p_k)/(\varepsilon_k p_j))^{\varepsilon j}\,(p_k/p_l)^{\varepsilon l}$ and $g(x)= (\varepsilon_l/\varepsilon_k)^{\varepsilon l}$, we obtain:

(15) $$\frac{dY(F_k)}{d\varepsilon_l} = F_k\left[\prod_{j\neq k,l}\left(\frac{p_k}{p_j}\frac{\varepsilon_j}{\varepsilon_k}\right)^{\varepsilon_j}\right]\left(\frac{p_k}{p_l}\right)^{\varepsilon_l}\left(\ln\frac{p_k}{p_l}\right)\left(\frac{\varepsilon_l}{\varepsilon_k}\right)^{\varepsilon_l} + F_k\left[\prod_{j\neq k,l}\left(\frac{p_k}{p_j}\frac{\varepsilon_j}{\varepsilon_k}\right)^{\varepsilon_j}\right]\left(\frac{p_k}{p_l}\right)^{\varepsilon_l}\frac{d\left(\left(\varepsilon_l/\varepsilon_k\right)^{\varepsilon_l}\right)}{d\varepsilon_l}$$

To obtain $d((\varepsilon_l\square\varepsilon_k\square^{\varepsilon l})/d\varepsilon_l$, we apply the differentiation rule $D((f(x)^{g(x)})= f(x)^{g(x)}[g'(x)\ln f(x)+g(x)f'(x)/f(x)]$ where $f(x)= \varepsilon_l \square\varepsilon_k$ and $g(x)= \varepsilon_l$. We thus obtain:

(16) $$\frac{d\left(\left(\varepsilon_l/\varepsilon_k\right)^{\varepsilon_l}\right)}{d\varepsilon_l} = \left(\frac{\varepsilon_l}{\varepsilon_k}\right)^{\varepsilon_l}\left(\ln\frac{\varepsilon_l}{\varepsilon_k} + \varepsilon_l\frac{1/\varepsilon_k}{\varepsilon_l/\varepsilon_k}\right) = \left(\frac{\varepsilon_l}{\varepsilon_k}\right)^{\varepsilon_l}\left(\ln\frac{\varepsilon_l}{\varepsilon_k}+1\right).$$

By substituting (16) in (15), we obtain:

(17) $$\frac{dY(F_k)}{d\varepsilon_l} = F_k\left[\prod_{j\neq k,l}\left(\frac{p_k}{p_j}\frac{\varepsilon_j}{\varepsilon_k}\right)^{\varepsilon_j}\right]\left(\frac{p_k}{p_l}\right)^{\varepsilon_l}\left(\frac{\varepsilon_l}{\varepsilon_k}\right)^{\varepsilon_l}\left(1+\ln\frac{p_k}{p_l}\frac{\varepsilon_l}{\varepsilon_k}\right).$$

Using (14), (17) can be reformulated as:

(18) $$\frac{dY(F_k)}{d\varepsilon_l} = Y\left(1+\ln\frac{p_k}{p_l}\frac{\varepsilon_l}{\varepsilon_k}\right).$$

From (12),

$$\frac{p_k}{p_l}\frac{\varepsilon_l}{\varepsilon_k}=\frac{F_l}{F_k},$$

which, substituted to the (17), allows to obtain

$$\text{(19)}\qquad \frac{dY(F_k)}{d\varepsilon_l}=Y\left(1+\ln\frac{F_l}{F_k}\right).$$

The higher is the equilibrium use of factor l in the production process, and hence the lower its market price, the higher is the effect of an increase of the elasticity ε_l on the output.

Equation (19) proofs the existence of technological congruence in the most general case of a Cobb-Douglas production function with n production factors. It seems clear that the unit of analysis plays a major role in assess in the relationship between inputs and outputs.

3. THE IMPLICATIONS OF TECHNOLOGICAL CONGRUENCE

The implications of technological congruence are far reaching and spread out in many important directions opening new perspectives in many debates and fields of investigation. Their tentative list follows with a brief analytical sketch.

3.1. Technological congruence and technological advance

The introduction of technological changes in different locations may have different effects according to the relative costs of production factors. A new technology may be actually more productive in a given country and less productive and consequently actually inferior to existing ones, in another country. Technological congruence impedes the objective ranking of technologies and questions the very notion of technological advance. A new technology can be considered superior or actually inferior to others only when the actual conditions of the local factor markets are taken into account (Abramovitz and David, 1996; Antonelli, 2003). All this implies that technological congruence makes the notion of technological advance local and not global.

3.2. Technological congruence and total factor productivity growth

Standard measures of total factor productivity growth assume that factor shares are constant (Solow, 1957). If factor shares change because of the introduction of new technologies that make possible a more intensive use of locally abundant factors total factor productivity measures are influenced (Bailey, Irz, Balcombe, 2004). In order to appreciate the effects of technological congruence it becomes necessary to distinguish between a shift and a bias effect (Antonelli, 2006). The bias effect consists in the increase of total factor productivity that stems from the better matching between the distribution of outputs elasticity and the factor markets. The bias effect consists in the consequences of the changes in the slopes of the maps of isoquants. The shift effect consists in the sheer changes in the position of the map of isoquants. A new technology may have positive shift effects and negative bias ones. The actual effect depends on the algebraic relationship between the two effects (Antonelli and Quatraro, 2010; Zuleta, 2012).

3.3. Technological congruence and the direction of technological change

Technological change is far from neutral. Much evidence confirms that technological change exhibits substantial directionality. Cliometric investigation confirms that the direction of technological change changes across time and across firms, industries and regions (Abramovitz and David, 1996). The notion of technological congruence enables to understand the incentives of firms and countries to try and direct the introduction of new technologies that make a more intensive use of locally abundant factors. Here the notion of technological congruence enables to make a major progress in the debate about the determinant of the so-called inducement mechanisms. There is a large and controversial literature on the direction of technological change (Ruttan, 1997 and 2001; Acemoglu, 2003 and 1010). The notion of technological congruence provides a new perspective to disentangle the key issues. Firms and countries have an incentive to direct the introduction of new technologies not to substitute inputs that have become more expensive as argued by John Hicks (1932) who revived the Marxian analysis of induced technological change, but to substitute inputs that are more expensive than others and to valorize the local availability of cheap production factors (David, 1975). The direction of technological change is successful when its bias enables to valorize the relative abundance of inputs in local factor markets. The search for technological congruence keeps the introduction of technological changes within corridors defined by the intensity of local availability of cheap production factors.

3.4. Technological congruence and the international division of labor

The international division of labor cannot be any longer regarded as the given result of an exogenous distribution of endowments. The specialization of countries in international markets can be considered as the result of a careful selection of appropriate technological corridors that enable to valorize the relative abundance of some inputs in local factor markets. The specialization of countries is the direct consequence of their ability to direct technological change towards the right ‘bias’. Hence the international specialization of both countries and firms is to a large extent endogenous. Countries and firms can shape their role in the international division of labor, both favoring the emergence of an appropriate bias that shapes intentionally the direction of technological change that takes into account the existing characteristics of internal factor markets, and implementing the supply of production factors that are most relevant in a given set of technologies (Habakkuk, 1962; Abramovitz and David, 1996; Comin and Hobijn, 2004).

3.5. Technological congruence, firms strategies and the emergence of innovation systems

The clear incentive of firms to try and specialize their activities so as to increase the output intensity of locally abundant inputs is likely to shape not only the individual strategies of each firm but also the emergence of local pools of collective knowledge. The local abundance of specific inputs, in fact, becomes a guiding factor that pushes all the firms co-localized to direct their generation of new technological knowledge towards complementary phases and components of a general production process that is more intensive in the same input locally abundant. The ricardian specialization of Portugal in wine and England in cotton can be seen as the result of the collective specialization of Portuguese and English firms, respectively, in the exploitation of dedicated and specific inputs that were locally abundant. The active search for complementarity helps the emergence of national and regional innovation systems centered upon the local endowments (Malerba, 2005). In this sense, differences in the local industrial architectures might be viewed as a natural consequence of technological congruence shaping a particular sectoral system.

3.6. Technological congruence and location

As a corollary of the above considerations, technological congruence that might and – for the efficiency reasons - should motivate the exploitation of the relative abundance of a productive factor in a certain location might be viewed as a novel factor determining the local concentration of economic activities around industrial clusters. Indeed, technological congruence directly determines the direction and the extent of external technological spillovers observable in a certain geographic location. The greater opportunity in terms of the availability of such external technological effects is perceived by the firms and motivates their location around the economic center (Feldman, 1999).

3.7. Technological congruence and the diffusion of innovations

The appreciation of the notion of technological congruence reinforces the supply school of analysis of the diffusion of innovations and reduces the appeal of the epidemic approach. Adoption takes place when and if the characteristics of the new technology are appropriate to the local context of action of potential adopters. Late adopters of new technologies should not necessarily regarded as ‘lazy’, but -on the opposite- as clever (conscious) agents that are able to assess carefully the actual matching between the characteristics of the new technology ad their specific conditions. Late adopters may be rational agents that are able to wait until the characteristics of the new technologies change and become closer to the specific conditions. Actually some countries and firms may decide that the poor levels of technological congruence of a new technology do not warrant its adoption (David, 1969; Stoneman and Battisti, 2010).

3.8. Technological congruence and supply policies

The grasping of the dynamics of technological congruence can help the design of economic policy directed at increasing the local supply of key production factors. Such intervention may become necessary: a) when a new superior technology introduced in country A with a large endowment of input X is actually most effective in country B where factor X is scarce because of the major positive shift effects that compensate for the negative bias ones; B) when the introduction and widespread diffusion of a new technology with a large output elasticity for a locally abundant input affects the derived demand for it and its market price. In both cases, X can be identified as a key input. In such conditions there is a strong incentive to make the supply of the key input X locally stronger so as to accommodate the increasing demand and contrast its negative effects on market prices. The sectoral architecture of economic systems plays a central role in providing the rest of the system with a large and cheap supply of key inputs. Industrial policy should favor the emergence of 'good' sectoral architectures and target the creation and strengthening of the local supply of the key intermediary factors. The same logic can help implementing an effective training policy aimed at supporting the selective creation of dedicated skills and specific types of human capital (Mohnen and Röller, 2005; Gehringer, 2011). Moreover, in the spirit of interdependences between sectors, it could be efficient to support a technological upgrading of a sector - even with a relatively lower degree of technological congruence – if this is crucial to the activities of another sector(s) with already high technological congruence.

3.9. Technological congruence and innovation policy

There is not a single, homogeneous frontier of technological advance upon which all countries and firms are equally localized. The relative endowments of production factor shape and limit the portion of the frontier upon which each agent or country has a true incentive to try and make an advance. Each agent should try and identify the direction of technological advance that suits more its specific factor endowments and specialize its research capabilities accordingly. The variety of research paths on the frontier of technological advance is intrinsically necessary as much as the variety of specializations in the international division of labor. Both are endogenous to the capability of firms, and countries at the system level, to identify the ways that make it possible to increase technological congruence as much as possible. Innovation policy in the first place should identify sector-specific levels of technological congruence. Subsequently, they should target the introduction of dedicated technologies able to increase the levels of technological congruence (Antonelli and Crespi, 2012). This should regard especially sectors considered as playing a crucial role in driving induced economic growth. Complementary to this, an intermediate goal of innovation policies requires building an efficient system of measures – targeting business aspects that are internal and external to the normal operating of the firm/industry - able to support the exploitation of technological congruence intrinsic in the system.

4. CONCLUSIONS

Technological congruence is a powerful tool that helps to grasping many aspects of the economics of growth accounting, international division of labor and structural change. Even after the appraisal of the endogenous growth models, it received little attention in the economic literature.. Its appreciation stems directly from the advances of the economics of innovation and its recent developments in understanding the endogenous determinants of the introduction and diffusion of technological changes. The levels of technological congruence are most relevant to influence the actual efficiency and to shape the competitive advantage (?) of firms and countries. The understanding of the determinants and effects of technological congruence can help to implement new effective strategies at the firm level and -at the system level- the design of selective industrial and labor policies directed at increasing the local supply of key inputs. More precisely, within a broad design of industrial policy for technological lead, innovation policies should be directed at favoring the introduction of new technologies that are better able to match and valorize the local factor endowments.

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