DETECTING TECHNOLOGICAL CATCH-UP IN ECONOMIC CONVERGENCE

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Abstract: Our aim is to address the problem of measuring how much of the convergence that we observe is due to convergence in technology versus convergence in capital-labour ratios, in the absence of data on the level of technology. To this aim, we first develop a growth model where technology accumulation in lagging economies depends on their propensity to innovate and on technological spillovers, and convergence is due *both* to capital deepening and to catch-up. We study the transitional dynamics of the model to show how to discriminate empirically among the following three hypotheses: (i) convergence due to capital deepening with technology levels uniform across economies, as in Mankiw, Romer and Weil (1992); (ii) convergence due to capital deepening with stationary differences in individual technologies, as in Islam (1995); (iii) convergence due to both catch-up and capital deepening (non-stationary differences in individual technologies. We show that, in the absence of TFP data, hypotheses (ii) and (iii) may be difficult to distinguish in cross-section or panel data. We suggest that discrimination can be nevertheless obtained by exploiting the fact that if heterogeneity is the source of catch-up, technology growth is not uniform across countries and the initial differences in technology levels may tend to decrease over time. Given this implication, one way to discriminate between (ii) and (iii) would be to test whether estimates of fixed-effects in sub-periods show the pattern implied by either hypothesis.

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1. Introduction

Technology differences and diffusion are likely to be important factors in convergence. As recent evidence shows, cross-country differences in total factor productivity (TFP) are wide in the Summer and Heston (1991) data set, so that "changes in relative TFP levels can have important effects on the steady-state income distribution" [Jones (1997), p. 148].[1] Testing whether relative TFP levels are changing – and whether these changes generate technology convergence, as implied by the catch-up hypothesis [Abramoviz(1986)] – is therefore of great practical importance.

In spite of this, one shortcoming of the empirical literature on growth concerns precisely the analysis of the impact of technology heterogeneity on convergence, as Bernard and Jones (1996), among others[2], have underlined. In particular, there are two very important lines of research convergence in which the joint role of technology heterogeneity and diffusion is neglected. The first is associated with the very influential paper by Mankiw, Romer and Weil (1992), in which systematic cross-country parametric heterogeneity of the production function is ruled out by assumption[3]. In the following we will refer to this assumption as "hypothesis (i)" about technology and convergence.

The second line of research is associated to Islam (1995). This paper represents a step forward on how to obtain reliable evidence on the role of technology differences in convergence using Solow's growth framework, in the absence of data on technology levels. Islam uses panel data estimates to test the hypothesis of homogeneity versus heterogeneity of the productivity shift parameter[4], and finds evidence in favour of the latter hypothesis. In Islam's paper, however, current technological differences are treated as if they were stationary ones, so that the hypothesis that they might be a source of technological catch-up is not explicitly considered or tested. We label this approach as "hypothesis (ii)".

As a consequence, we simply do not know enough about "how much of the convergence that we observe is due to convergence in technology versus convergence in capital-labour ratios" [Bernard and Jones (1996), p. 1043]: in the current convergence literature, this important question does not seem capable to attract the attention it deserves.[5] One reason behind this insufficient attention is perhaps due

[1] See also Hall and Jones (1999).
[2] On the importance of considering technology diffusion in convergence, see also Parente and Prescott (1994), Jones (1997), de la Fuente (1997) and Lee, Pesaran and Smith (1998).
[3] More in detail, Mankiw, Romer and Weil assume that country-specific (non strictly technological) shocks exist, but they can be regarded as random disturbances independent of the explanatory variables that control for the differences in the steady-state values of per-capita income. For critical viewpoints on the role of technology in the convergence analysis of Mankiw, Romer and Weil (1992), see also Islam (1998) and Paul Romer's comment in Snowdown and Vane (1999).
[4] See also Islam (1998).
[5] A further confirmation of this is given by a third, separate line of research, in which technology diffusion is regarded as the crucial source of convergence [for instance, Dowrick and Nguyen (1989) and Fagerberg and Verspagen (1996)]. Again, the whole observed convergence is assigned to one source (catch-up, in this case) in a context where the other (capital deepening) is neglected on a priori grounds, rather than tested.

to the fact that it is difficult to distinguish empirically between those two sources of convergence[6], especially when reliable data on technology levels are not available[7].

In this paper we search for a solution to this specific problem – how to distinguish between capital deepening and technology catch-up in convergence analysis, in the absence of TFP data. The strategy we adopt is to develop a simple model built around a more general (but often neglected, as we have seen) "hypothesis (iii)" about convergence and technology[8] – namely, the hypothesis that convergence might be due to both technology catch-up and capital deepening. An advantage of using this type of model is that the other hypotheses can be easily obtained as special cases and therefore evaluated empirically within the same framwork.

In the model developed in this paper capital accumulation proceeds as in Solow's growth model, while technology accumulation depends on a propensity to innovate, which may vary across economies. Stationary technology gaps can emerge as the result of such differences. During the transition to balanced growth, technology diffusion is a function of the difference between stationary and current gaps. The influence exerted by capital deepening and catch-up in convergence along the transitional path can be identified.

While several growth models based on endogenous innovation exist in the literature[9], they are not generally concerned with obtaining simple transitional dynamics in which convergence is due to the simultaneous presence of capital deepening and technological catch-up[10]. A different and simpler approach has been recently proposed in de la Fuente (1995) and Bernard and Jones (1996), in which a model with decreasing returns to capital is augmented with exogenous differences in the countries' ability to adopt new technology. Our model differs from de la Fuente's in two major respects. First, as in Shell (1966)[11], the flow of new technology in each period is proportional to the amount of resources endogenously allocated to innovation. Second, the impact of any given technology gap on technology growth in a follower country is proportional to its propensity to innovate (or imitate). In this respect, our formulation is closer to the one used in Benhabib and Spiegel (1994) to assess the impact of the stock of human capital on the diffusion of technology. As for Bernard and Jones (1996), the main differences are that in our model the growth rate of the leader economy is endogenous, and that we

[6] As it is well known, simple models of catch-up (in which the sources of technology accumulation are left unexplained) and the Solow model may turn out to yield predictions that are indistinguishable in cross-section and panel data [Barro and Sala-i-Martin (1995), p. 275].
[7] As de la Fuente puts it, "there are few econometric studies in the convergence literature dealing with [the catch-up hypothesis], probably because it is difficult to come up with a reliable index of technical efficiency" [de la Fuente (1997), p. 63n].
[8] Other formulations are of course possible in which catch-up plays an important role in generating convergence in the absence of diminishing returns to capital [see Pugno (1995) for a very useful comparison of different models].
[9] Aghion and Howitt (1998) for a recent exhaustive survey.
[10] See for instance Barro and Sala-i-Martin (1997).
[11] The growth model we use to characterise the "leader" economy is similar to the model developed in Shell's seminal paper. As is well known, that model does not have a balanced growth path. Moreover, its stable branch leading to the steady state

make specific statements on what determines a country's ability to adopt new technology. Moreover, and crucially for our aims, we study the transitional dynamics explicitly.

We use this model to specify what evidence we need in order to distinguish among the three hypotheses listed above, in the absence of reliable indexes of individual technology levels.[12] The transitional dynamics of our model shows the following. While distinguishing between hypothesis (i) (no technological heterogeneity) v hypotheses (ii)-(iii) is a relatively simple task, assessing the precise role played by technological heterogeneity – that is, distinguishing between hypotheses (ii) and (iii) – turns out to be far less simple. In particular, detecting a positive correlation between growth rates of per-capita income and propensities to innovate does not yield unambiguous evidence in favour of hypothesis (iii). The reason is that if individual propensities to innovate determine stationary technological differences, the former may act as a proxy for the latter whenever catch-up is absent or exhausted. More generally, we show that the panel data formulations corresponding to the two hypotheses might yield very similar results[13]. To the best of our knowledge, this problem has not received the attention it deserves in the empirical literature on convergence.[14]

We also show how identifying other testable implications can solve this problem. In particular, under hypothesis (iii) technology growth is not uniform across countries so that the initial level differences may tend to decrease over time. Therefore, the variance of the individual technology levels is likely to be different from its steady-state value during the transition. On the contrary, under hypothesis (ii) the prediction is instead that such a variance is constantly at its stationary value – abstracting from random disturbances. Therefore, as long as the variance of the individual intercepts obtained by means of panel data estimates yields an approximate measure of the degree of technology heterogeneity, the pattern of such a variance over subsequent periods could be used to distinguish between hypothesis (ii) and (iii). Other discriminating implications do exist. For instance, hypothesis (iii) alone implies the existence of an increasing positive correlation between the individual technology levels and the propensity to innovate along the transitional path. Moreover, the correlation between the individual intercepts and the growth rates of per-capita income is positive under hypothesis (ii) [Islam

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has unrealistic economic implications. Both shortcomings are avoided in our model by adopting labour-augmenting technological progress.

[12] de la Fuente (1995) discusses how to discriminate between the competing hypotheses using several variables as proxies of the initial technology levels. He does not discuss how to interpret the evidence when technology levels are unobservable and reliable proxies are not available.

[13] Islam (1995) has shown that estimating a convergence equation by means of a fixed-effect panel data estimator such as LSDV allows for testing for the presence of technology heterogeneity. In such a formulation, the individual intercepts are regarded as an indirect measure of the unobservable technology levels.

[14] An implication of this problem is that, on one hand, the evidence of the type discussed in Islam (1995) should not be regarded as conclusive evidence that technology differences across economies are semi-permanent. On the other hand, hypothesis (ii) is not necessarily rejected by the existence of a positive correlation between growth rates and some index based on R&D and patents data, which may approximate the propensity to innovate. See Fagerberg, Verspagen and Caniels (1997), among many others, for examples in which this type of evidence is interpreted as corroborating the hypothesis that convergence is due to catch-up, the strength of which in turns depend on the innovative efforts of each economy. See also Fagerberg, Verspagen (1996).

(1995)], and negative under hypothesis (iii). We conclude that in the absence of data on technology levels a carefull analysis of the estimated individual intercepts should significantly enhance our chances of discriminating between the two hypotheses.

The rest of the paper is organised as follows. In section 2 we discuss our model. In section 3 we study its transitional dynamics and discuss how to discriminate among the competing hypotheses about the sources of convergence. Conclusions are in section 4.

2. A growth model with exogenous propensity to innovate

In this section we develop a model in which the long run growth rate of the leader economy depends on its propensity to innovate, and in which the technological catch-up of the follower depends on its own propensity to innovate. The model is extremely simple in its characterisation of the activity of innovation, but still detailed enough as far as our aim is concerned. Stationary differences in technology levels emerge as long as propensity to innovate differs across economies. Similarly to de la Fuente (1995), these differences are taken as given, and no attempt is made to explain how they come about and what policies can modify a given situation. Since our aim is to evaluate the consequences of technology heterogeneity on convergence, this limited approach suits us well enough.

Our model differs from de la Fuente's (1995) in several respects. In de la Fuente's model, accumulation of technology takes place according to $\dot{A}/A = gq + hb$, where $\dot{A}/A$ is the growth rate of technology, q is the proportion of GDP invested in R&D, and b is a measure of the technology gap, g and h are constants. We modify this formulation in two ways. The first concerns the relation between the growth rate and the propensity to innovate both in the leader and in the follower countries. We put this relation on what we regard to be more solid economic grounds by making the flow of innovation proportional to a measure of the amount of resources endogenously allocated to R&D in each period (see section 2.1 below). In this respect, our model is close to Shell (1966). The second concerns the mechanism of catch-up. In the above formulation, the impact of a given gap on a country's rate of innovation is independent of the resources used to innovate (or imitate). This formulation conflicts with a large literature on catch-up, where strong emphasis is placed on how some characteristics of the follower economies determine how much of the potential catch-up is actually achieved [Abramovitz (1986)]. We propose a different formulation, similar to the one Nelson and Phelps (1966) have used to analyse the role of the stock of human capital in the catch-up process [see also Benhabib and Spiegel (1994), who use a similar idea in a context in which endogenous growth is allowed for]. We address this point in details in section 2.2.

In the following, we first describe growth in the leader country, and then we turn to the mechanism of catch-up.

2.1 The leader economy

We assume that good Y is produced by means of a Cobb-Douglas technology:

$$Y = K^{a} (AL)^{1-a} , \tag{2.1}$$

where K is capital, L labour and A an index of technology . Some definitions associated with this production function will be used often in the following. They are as follows: $k \equiv K/L$, $z \equiv K/AL$, $y \equiv Y/L = k^{a} A^{1-a} = z^{a} A$, $y' \equiv y/A = z^{a}$.

As for how innovation is accumulated, a propensity to innovate exists defined as $q \equiv R/Y$, where R is the total amount of the existing resources allocated to R&D[15], with $0 \leq q < 1$. Technological knowledge increases in proportion to R, according to the following relation:

$$\dot{A} = \left(\frac{R}{L}\right)^{e} = \left(\frac{qY}{L}\right)^{e}, \tag{2.2}$$

where $0 < e \leq 1$. In the following, we assume that $e = 1$, so that endogenous growth is obtained, with the growth rate being a function of the propensity to innovate. Using (2.1) in (2.2), we have:

$$\frac{\dot{A}}{A} = q\, k^{a} A^{-a} = qz^{a} . \tag{2.3}$$

Technological progress is therefore a function of the per-capita amount of resources allocated to innovation in the economy[16]. Countries with similar propensities to innovate but with different levels of per-capita output have different innovation rates.

To characterise the long run rate of innovation in this economy, we now turn to the endogenous determination of the stationary value of z, the index of capital per efficiency unit. For the sake of simplicity, we assume that $(d + n)=0$[17]. Then:

$$\frac{\dot{z}}{z} = sz^{a-1} - qz^{a} , \tag{2.4}$$

where s is the exogenous saving rate, $0<s<1$. For consumption to be allowed in each period, the restriction $(s + q) < 1$ is required. In steady-state,

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[15] Technology in this model is a pure public good available for free to all existing firms. As a consequence, it would be more appropriate to define our "propensity to innovate" as the fraction of resources allocated to innovation by the state, through some non-market mechanism [see Shell (1966)]. We do not elaborate on this since we are interested in the consequences of a given heterogeneity in innovative activity, rather than in the mechanism that generate such heterogeneity.

[16] An alternative would be to make the flow of innovation depend on the absolute value of R. This however would generate a counterfactual growth effect associated to the scale of the labour force. This problem (as well as the solution adopted in the text) is typical of endogenous models based on simple learning-by-doing mechanisms [see Barro e Sala-i-Martin (1995) p. 151-2].

(2.5) $$\tilde{z} = \frac{s}{q}$$

and therefore:

(2.6) $$\frac{\dot{A}}{A} = q^{1-a} s^{a} .$$

In steady-state the leader economy grows at a constant rate endogenously determined by the parameters that describe the technology and the propensities to invest in physical capital and in innovation.

2.2 The follower economy

Few changes are necessary to characterise the follower economy. As we have suggested above, we would like to model the dependence of the intensity of technological spillovers accruing from the leader country on the resource allocated by the follower to innovate or imitate. One way of modelling this feature is simply by multiplying the propensity to innovate by a measure of the current technology gap, as in the following formulation:

(2.7) $$\frac{\dot{A}}{A} = q\left(\frac{A^*}{A}\right) z^{a}$$

where now * refers to the leader. Here the impact of a given gap on the growth rate is proportional to the follower's effort in innovation. In the absence of any effort, there are no spillovers to be gained, and no economic growth[18]. In the following we assume that $0 < q \leq q^*$. Then

(2.8) $$\frac{\dot{z}}{z} = s z^{a-1} - q\left(\frac{A^*}{A}\right) z^{a}$$

and the stationary value of *z* is:

(2.9) $$\tilde{z} = \frac{s}{q}\left(\frac{A^*}{A}\right)^{-1}$$

where $0 < s \leq s^*$. The long run rate of innovation is equal to:

(2.10) $$\frac{\dot{A}}{A} = q\left(\frac{s}{q}\right)^{a}\left(\frac{A^*}{A}\right)^{1-a}$$

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17 See Appendix A.

18 For a similar assumption in a different context – where technology adoption depends on the level of the stock of human capital – see Benhabib and Spiegel (1994). See also Bernard and Jones (1996).

It is now possible to define the stationary value of the technology gap as a function of the exogenous parameters of the model.

2.3 Intertemporal equilibrium

With $q > 0$, the stationary value of A^*/A ($\tilde{A}$ hereafter) is:

$$\tilde{A} = \frac{q^*}{q}\left(\frac{s^*}{s}\right)^{\frac{a}{1-a}}. \tag{2.11}$$

Clearly, if all the parameters are uniform across the economies, the stationary value of the gap is one. Differences in the propensity to innovate ($q^* > q$) translate into the leader having a stationary technological advantage over the follower.

As for the values of $\tilde{z}$ and $\tilde{g}$, we use (2.11) respectively in (2.9) and in (2.10). As regards (2.9), we find:

$$\tilde{z} = \frac{s}{q^*}\left(\frac{s^*}{s}\right)^{\frac{-a}{1-a}}. \tag{2.12}$$

And therefore:

$$\frac{\tilde{z}^*}{\tilde{z}} = \left(\frac{s^*}{s}\right)^{\frac{1}{1-a}}. \tag{2.13}$$

Economies with different propensities to innovate, but similar propensity to save, end up with the same stationary value of k/A.

As for $\tilde{g}$, we find $\tilde{g} = q^{*1-a} s^{*a} = \tilde{g}^*$. In the long run, the two economies grow at the same rate (with the growth rate of the follower converging to that of the leader). Finally, the relative per-capita income in the long run is equal to $\tilde{y}^*/\tilde{y} = (q^*/q)(s^*/s)^{\frac{2a}{1-a}}$.

Dynamic stability

The system is globally stable around its intertemporal equilibrium defined by the stationary values of z, z^* and of A^*/A. We analyse dynamic stability by means of a two-variable (z/z^*, A^*/A) phase diagram. Given equations (2.4) and (2.8) above, the condition $\dot{z} = \dot{z}^* = 0$ implies:

$$\frac{z}{z^*} = \frac{sq^*}{s^*q}\left(\frac{A^*}{A}\right)^{-1}. \tag{2.14}$$

The isocline defined by (2.14) is negatively sloped and convex. Given the equations (2.3) and (2.7) above, the condition $d\left(A^*/A\right)/dt = 0$ implies:

$$(2.15) \qquad \frac{z}{z^*} = \left(\frac{q^*}{q}\right)^{\frac{1}{a}} \left(\frac{A^*}{A}\right)^{-\frac{1}{a}}.$$

The isocline defined by (2.15) is also negatively sloped and convex. Therefore, the dynamic stability of the intertemporal equilibrium depends on how the two functions intersect in the phase space. Let us define f_z the right hand side of (2.14), f_A the right hand side of (2.15). Figure 1 shows the case in which the intertemporal equilibrium is globally stable. Since a <1, the case depicted in the figure is indeed the relevant one for our model.

More formally, let us define $f \equiv f_A / f_z$. Figure 1 shows that global stability implies $df / d\left(A^*/A\right) < 0$. This condition is always satisfied in our model since $f = p\left(A^*/A\right)^{\frac{a-1}{a}}$, where $p \equiv \left(s^*/s\right)\left(q^*/q\right)^{\frac{1-a}{a}}$.

A follower economy off its steady-state is generally characterised by $z/z^* < \tilde{z}/\tilde{z}^*$ and $A^*/A > \tilde{A}$ (as for instance in point B in Figure 1). As a consequence, its convergence path is influenced simultaneously by the capital deepening mechanism emphasised by the Solow model, and by the technological catch-up process. In the following section, we use a log-linear approximation of the system to assess the role of each component along the transitional path.

3. Transitional dynamics

In this section, our aim is to assess the influence exerted by the two effects on labour productivity growth in a cross-section or panel of economies. To do this, we start by log-linearizing the system around the steady-state values of z and A^*/A. Since our purpose is not to identify the parameters of the model exactly, but rather to show how the presence of catch-up can be detected, in the following we present a simplified version of the transitional dynamics of our model. This version is obtained by ignoring the interaction between z and the gap along the transitional path. While some precision is lost, the picture we get is sufficiently detailed for our purpose.

We start with the log-linearization of the growth rate of z around its stationary value. From equation (2.8), we have:

$$(3.1) \qquad \frac{\dot{z}}{z} = s z^{a-1} - g_A$$

where $g_A \equiv \dot{A}/A$. Keeping g_A constant for the time being, log-linearization yields:

(3.2) $$\frac{d \ln y'}{dt} = (a-1)\tilde{g}^*[\ln y'(t) - a \ln \tilde{z}]$$

where $y' \equiv y/A$. After finding the solution to this differential equation and some manipulations (see Appendix B) we get:

(3.3) $$\ln y(t_2) - \ln y(t_1) = g_A + \left(1 - e^{-(1-a)\tilde{g}^* t}\right) a \ln\left(s/q^*\right) - \left(1 - e^{-(1-a)\tilde{g}^* t}\right) \ln y(t_1) + \left(1 - e^{-(1-a)\tilde{g}^* t}\right) \ln A(t_1)$$

where t_1 is an initial point of time, $t_2 > t_1$, $t \equiv t_2 - t_1$ and $g_A \equiv \ln A(t_2) - \ln A(t_1)$. In cross-section, t_2 and t_1 are respectively the final and the initial period. In panel data formulation, t defines the length of the time spans in which the total period of observation is divided. Equation (3.3) shows the growth rate of labour productivity between two periods as a function of the distance of *z*, in the initial period, from its stationary value. In other words, it describes the capital deepening component of convergence – the one emphasised by the Solow model.

As observed earlier, another component is simultaneously at work. This component enters equation (3.3) through the term g_A, which is a function of the distance of the gap in the initial period from its stationary value $\tilde{\mathrm{A}}$. This relationship can be made precise as follows. Assuming that the leader is in steady-state, the rate of change of the gap measures the deviation of the current rate of technology growth in the follower country from its steady-state rate: $d \ln\left(A^*/A\right) = \tilde{g}^* - qz^a\left(A^*/A\right)$. Taking a log-linear approximation of $d \ln\left(A^*/A\right)$ around its steady-state, we have:

(3.4) $$d \ln\left(A^*/A\right) = -\tilde{g}^*\left[\ln\left(A^*(t)/A(t)\right) - \ln \tilde{\mathrm{A}}\right].$$

Using the general solution of (3.4), after a few passages (see Appendix B) we find:

(3.5) $$\ln A(t_2) - \ln A(t_1) = \tilde{g}^* t + \left(1 - e^{-\tilde{g}^* t}\right) \ln\left[A^*(t_1)/A(t_1)\right] - \left(1 - e^{-\tilde{g}^* t}\right) \ln \tilde{\mathrm{A}}\ .$$

Finally, substituting (3.5) in (3.3) we get an equation in which both components affecting convergence are present simultaneously.

(3.6) $$\begin{aligned} \ln y(t_2) - \ln y(t_1) = \tilde{g}^* t + \left(1 - e^{-\tilde{g}^* t}\right) \ln\left[A^*(t_1)/A(t_1)\right] + \left(1 - e^{-(1-a)\tilde{g}^* t}\right) \ln A(t_1) + \\ + \left(1 - e^{-(1-a)\tilde{g}^* t}\right) a \ln\left(s/q^*\right) - \left(1 - e^{-(1-a)\tilde{g}^* t}\right) \ln y(t_1) - \left(1 - e^{-\tilde{g}^* t}\right) \ln \tilde{\mathrm{A}} \end{aligned}$$

Equation (3.6) can be used to assess the role of heterogeneous propensity to innovate and of technological catch-up in convergence. Two different cases are discussed below. In both cases, we assume that measures for the propensity to innovate are available. However, while in the first case an index of total factor productivity does exist, in the second it does not. Detecting catch-up in the second case turns out to be a far more complex task, even when the propensity to innovate q of individual economies can be measured accurately – as we assume it is the case from now on.

Before discussing the two cases in detail, we simplify the notation with no loss of generality by setting all individual countries' propensity to save equal to the leader's one, s^*. In this case, $\tilde{A} = q^*/q$ [see (2.12)] and $\tilde{z} = s^*/q^*$ [see (2.13)] in all economies. Modifying equation (3.6) accordingly, we obtain:

$$\text{(3.7)} \quad \begin{aligned} \ln y(t_2) - \ln y(t_1) = \tilde{g}^* t + \left(1 - e^{-\tilde{g}^* t}\right)\ln\left[A^*(t_1)/A(t_1)\right] + \left(1 - e^{-(1-a)\tilde{g}^* t}\right)\ln A(t_1) + \\ + \left(1 - e^{-(1-a)\tilde{g}^* t}\right)a \ln\left(s^*/q^*\right) - \left(1 - e^{-(1-a)\tilde{g}^* t}\right)\ln y(t_1) - \left(1 - e^{-\tilde{g}^* t}\right)\ln\left(q^*/q\right) \end{aligned}$$

3.1 Detecting technological catch-up when TFP data are available

In case total factor productivity can be measured accurately, equation (3.7) can be rewritten as:

$$\text{(3.8)} \quad \ln y(t_2) - \ln y(t_1) = u + \left(e^{-\tilde{g}^* t} - e^{-(1-a)\tilde{g}^* t}\right)\ln A(t_1) - \left(1 - e^{-(1-a)\tilde{g}^* t}\right)\ln y(t_1) + \left(1 - e^{-\tilde{g}^* t}\right)\ln q \ ,$$

where

$$u \equiv \tilde{g}^* t + \left(1 - e^{-\tilde{g}^* t}\right)\ln A^*(t_1) + \left(1 - e^{-(1-a)\tilde{g}^* t}\right)a \ln s^* - \left(2 - e^{-\tilde{g}^* t} - e^{-(1-a)\tilde{g}^* t}\right)\ln q^* .$$

Equation (3.8) shows that simple cross-section regressions can be used in this specific case[19], with u being defined as constant across individual economies. The presence of a catch-up process would be detected by a significantly negative coefficient of $\ln A$ and, in the case that the propensity to innovate is not uniform, by a significantly positive coefficient of $\ln q$. The other competing hypotheses considered above would be at odd with such an outcome. First, hypothesis (i) implies that $\ln A$ is uniform across all economies at all periods, included the initial one. Moreover, since technology is assumed to be exogenous, the propensity to innovate is not an explanatory variable of the observed differences in the growth rates of per-capita income. Second, the "stationary technological differences" hypothesis adopted by Islam (1995) implies that $\ln q$ is again not relevant (on this more below), and that $\ln A$ is expected to be significantly positive.

3.2 Detecting technological catch-up when TFP data are not available

More complex is the interpretation of the cross-sectional or panel evidence whenever data for TFP are not available, especially as far as discriminating between hypotheses (ii) and (iii) is concerned, as we will see presently.

A preliminary problem is how to estimate (3.7) in the current case. Given the presence of unobservable technology heterogeneity, we should use a dynamic panel data model fixed-effects, since such individual intercepts would yield an indirect measure of the technology level of each economy [Islam (1995)]. Let us rewrite (3.7) using a panel data formulation:

$$\ln y_{it} - \ln y_{i,t-1} = m_{it} + k_t - b \ln y_{i,t-1} + j \ln q_{i,t-1} + w_{it}, \tag{3.9}$$

where $k_t \equiv \tilde{g}^* t + \left(1 - e^{-\tilde{g}^* t}\right)\ln A^*(t_1) + \left(1 - e^{-(1-a)\tilde{g}^* t}\right)a \ln s^* - \left(2 - e^{-\tilde{g}^* t} - e^{-(1-a)\tilde{g}^* t}\right)\ln q^*$, $\ln y_{it} \equiv \ln y(t_2)$, $\ln y_{i,t-1} \equiv \ln y(t_1)$, $b \equiv 1 - e^{-(1-a)\tilde{g}^* t}$, $j \equiv 1 - e^{-\tilde{g}^* t}$ and $m_{it} \equiv \left(e^{-\tilde{g}^* t} - e^{-(1-a)\tilde{g}^* t}\right)\ln A(t_1)$. In this formulation, k_t varies across time periods and is constant across individual economies, m_{it} describes the degree of technology heterogeneity at a certain point in time, and w_{it} is the error term with mean equal to zero. We should soon notice that m_{it} is not a strictly time-invariant individual intercept,[20] so that the use of fixed-effect estimators in this case could be problematic.[21] We will come back to this below. For the time being let us assume that fixed-effects (LSDV) estimates of (3.9) can be obtained, with the individual intercepts yielding an approximate measure of m_{it}. For the sake of our discussion on how to distinguish among the various hypotheses, let us also assume that the signs of the coefficients of the explanatory variables are significant and in accordance with the predictions of the model.[22]

What conclusions should we draw from this type of evidence? First, since hypothesis (i) implies that the propensity to innovate is irrelevant for convergence analysis, it predicts that its coefficient is zero. So we can rule out hypothesis (i) in favour of the other hypotheses. Second, since (3.9) is obtained under hypothesis (iii), the above quoted result would clearly support this hypothesis. However, it also yields support for hypothesis (ii), so that at this stage the latter cannot be ruled out in favour of hypothesis (iii).[23] To see how this problem arises, the main step is to impose that technology diffusion is exhausted in our model [hypothesis (ii)], so that convergence is due entirely to capital-deepening (see point C in Figure 1). Under this assumption, $A^*(t)/A(t) = \tilde{A} = q^*/q$ in each period of time (including t=0), $\ln A(t_1) = \ln A(0) + \tilde{g}^*(t_1)$, and the following panel data formulation can be obtained:

$$\ln y_{it} - \ln y_{i,t-1} = r_i + c_t - b \ln y_{it-1} + v_{it} \tag{3.10}$$

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19 Assuming that the other unobservable variables are homogeneous across economies.

20 Under hypothesis (iii) the initial degree of technology heterogeneity cannot be regarded as strictly time-invariant. The reason is that technology diffusion is present, technology growth rates differ along the transitional path leading to their common steady-state value. Consequently, m_{it} includes the term $A(t_1)$ and cannot be properly defined as an individual intercept.

21 The problem we discuss here is different from the one raised by Lee, Pesaran and Smith (1998) in their comment on Islam (1995) about the use of panel data for convergence analysis. The approach they propose is based on the idea that technology growth rates tend to differ in the long- as well as in the short-run.

22 We obtain an outcome of this type using data on 109 European regions, 1980-93. See Paci and Pigliaru (1999).

23 To the best of our knowledge, up to now this problem has not yet been discussed in the empirical literature on convergence.

where $r_i \equiv \left(1-e^{-(1-a)\tilde{g}^* t}\right)\ln A(0)$, $c_t \equiv \tilde{g}^*\left(t_2 - e^{-(1-a)\tilde{g}^* t} t_1\right) + \left(1-e^{-(1-a)\tilde{g}^* t}\right) a \ln\left(s^*/q^*\right)$ and v_{it} is the error term with mean equal to zero. Notice that in this case the initial distribution of technology levels correctly reflects time-invariant individual differences, because the growth rate of technology is now assumed to be uniform across economies. As a consequence, r_i can be properly defined as an individual fixed-effect [Islam (1995), p. 1149].

The source of our problem can be easily unveiled now. Since under hypothesis (ii) technological differences are supposed to be at their stationary values $\tilde{\mathrm{A}} = q^*/q$ [24], then in principle $A(0)$ and q are perfectly correlated across economies. As a consequence, a significant positive value of j does not yield clear-cut evidence in favour of the hypothesis that technology diffusion is part of the observed convergence. [25] All we could say at this stage is that technology heterogeneity, due to differences in propensity to innovate, is relevant for convergence analysis.

To test whether technology diffusion is active or exhausted, we have to search for other distinct testable implications of the model under the two alternative hypotheses. To this aim, consider again the term m_{it} associated with hypothesis (iii). We have already noticed that m_{it} cannot be regarded as a proper fixed-effect, so that we cannot obtain reliable indirect measures of it by means of the individual intercepts in LSDV estimates over a long period of time. However, suppose that splitting the whole period under observation in several sub-periods made m_{it} a semi-permanent term in (3.9). This is a crucial assumption for our purposes, because in this case we could obtain LSDV estimates of (3.9) for properly defined sub-periods, and then use the estimated individual intercepts to test the following implications of the model.

First, since under hypothesis (iii) technology gaps are not at their stationary values, in general we should expect that $s_m^2 \neq \tilde{s}_m^2$. [26] As a consequence, convergence of s_m^2 to its stationary value should be detectable over subsequent periods if hypothesis (iii) is true – abstracting from random disturbances. On the other hand, under hypothesis (ii) s_r^2 is time-invariant, since – abstracting again from random disturbances – it is assumed to be at its steady-state value $\tilde{s}_r^2$. Second, the correlation between the individual intercepts and the growth rates of y is positive under hypothesis (ii) [Islam (1995)], and negative under hypothesis (iii). Finally, under hypothesis (iii) the correlation between the fixed-effects

[24] Recall that we are assuming that the propensity to save is uniform across all economies.

[25] More generally, finding that a technological variable such as R&D or patents exert a statistically significant positive effect on growth does not offer indisputable evidence that catch-up is part of the observed convergence. See Fagerberg, Verspagen and Caniels (1997) and Fagerberg and Verspagen (1996), among many others, for a different viewpoint on the interpretation of evidence of this type.

[26] However, in the absence of "absolute convergence" in technology levels the case $s_a^2 = \tilde{s}_a^2$ is not ruled out (similarly, *b*-convergence does not necessarily imply s-convergence unless steady-state values are uniform across individuals).

and the propensity to innovate should increase over time, as the system approaches its balanced groth path.

Estimating (3.9) [and (3.10)] by means of LSDV regressions over different sub-periods should therefore significantly enhance our chances of discriminating between the two hypotheses.[27]

4. Conclusions

In this paper we have developed a simple growth model where technology accumulation in lagging economies depends on their propensity to innovate and on inter-regional spillovers, and convergence is due to both capital-deepening and catch up. We have used the model to show how to generate unambiguous evidence on the role of technology diffusion in the observed convergence.

The transitional dynamics of our model shows that, in the absence of data on TFP, the most compelling task is to discriminate between the catch-up case and the alternative case based on the existence of stationary technology differences. Future research should address this important empirical problem along the lines suggested in section 3, where we have showed that the pattern of the fixed-effects in panel data regressions can be usefully analysed in order to distinguish between the two hypotheses.

As for the model of growth used in this paper, one interesting development would be to explore the possibility that the stock of human capital take part in the determination of the stationary technology gap – as in Benhabib and Spiegel (1994) –, together with the propensity to innovate analysed in this paper. Finally, the possibility that there exist a spatial component in the distribution of the propensity to innovate across individual economies should also be considered within the framework adopted here.

References

Aghion P. and Howitt P. (1998), *Endogenous growth theory*, Boston: MIT Press.

Abramovitz M. (1986), Catching-up, forging ahead and falling behind, *Journal of Economic History*, 46, 385-406.

Barro R. and Sala-i-Martin X. (1995), *Economic growth*, New York: McGraw-Hill.

Barro R. and Sala-i-Martin X. (1997), Technological diffusion, convergence and growth, *Journal of Economic Growth*, 2, 1-26.

[27] The use of LSDV estimates for convergence analysis has been criticised by Durlauf and Quah (1999) on the grounds that allowing $A(0)$ to differ across economies makes it particularly difficult to understand whether ***b***-convergence implies a reduction of the gap between the poor and the rich (p. 52-3). This criticism does not necessarily apply to our case, in which we concentrate on how to discriminate between two sources of convergence.

Benhabib J. and Spiegel M. (1994), The role of human capital in economic development: evidence from aggregate cross-country data, *Journal of Monetary Economics*, 34, 143-73.

Bernard A.B. and Jones C.I. (1996), Technology and convergence, *Economic Journal*, 106, 1037-44.

de la Fuente (1995), Catch-up, growth and convergence in the OECD, CEPR Discussion Paper No. 1274.

de la Fuente (1997), The empirics of growth and convergence, *Journal of Economic Dynamics and Control*, 21, 23-77

Dowrick S. and Nguyen D. (1989), OECD comparative economic growth 1950-85: catch-up and convergence, *American Economic Review*, 79, 1010-30.

Durlauf S.N. and Quah D.T. (1999), The new empirics of economic growth, Centre for economic Performance Discussion Paper no. 384 (Final version February 1999).

Fagerberg J. and Verspagen B. (1996), Heading for divergence. Regional growth in Europe riconsidered, *Journal of Common Market Studies*, 34, 431-48.

Fagerberg J., Verspagen B. and Caniels M. (1997), Technology, growth and unemployment across European regions, *Regional Studies*, 31, 457-466.

Hall R.E. and Jones C.I. (1999), Why do some countries produce so much more output per worker than others?, *Quartely Journal of Economics*, 114, 83-116.

Islam N. (1995), Growth empirics: a panel data approach, *Quarterly Journal of Economics*, 110, 1127-70.

Islam N. (1998), Growth empirics: a panel data approach – A reply, *Quarterly Journal of Economics*, 113, 325-9.

Jones C.I. (1997), Convergence revisited, *Journal of Economic Growth*, 2, 131-153.

Lee K., Pesaran M.H. and Smith R. (1998), Growth empirics: a panel data approach – A comment, *Quarterly Journal of Economics*, 113, 319-24.

Mankiw N.G., Romer D. and Weil D. (1992), A contribution to the empirics of economic growth, *Quarterly Journal of Economics*, 107, 407-37.

Nelson R.R. and Phelps E.S. (1966), Investment in humans, technological diffusion, and economic growth, *American Economic Review*, Papers and Proceedings 61, 69-75.

Paci R. and Pigliaru F. (1999), Technological catch-up and regional convergence in Europe, *Contributi di Ricerca Crenos*, 99/9

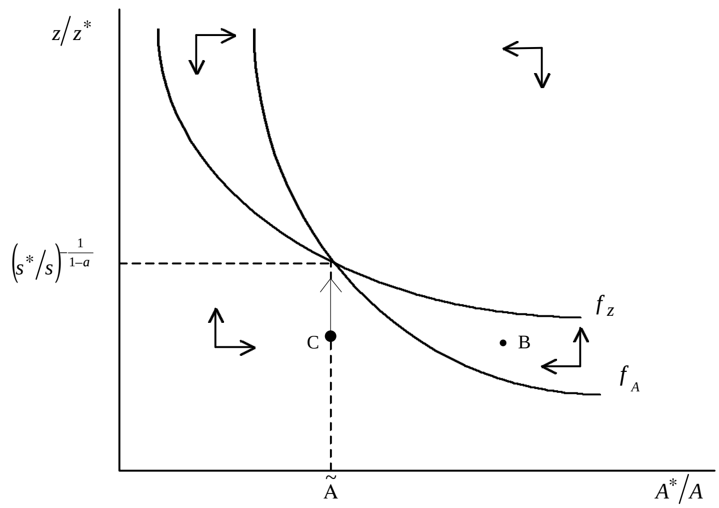
Parente S.L. and Prescott E.C. (1994), Barriers to technology adoption and development, *Journal of Political Economy*, 102, 298-321.

Pugno M. (1995), On competing theories of economic growth: cross-country evidence, *International Review of Applied Economics*, 9, 249-274.

Snowdown B. and Vane H. (eds) (1999), *Conversations with economists. Interpreting macroeconomics*, Cheltenham: Edward Elgar, forthcoming.

Shell K. (1966), Toward a theory of inventive activity and capital accumulation, *American Economic Review*, Papers and Proceedings 61, 62-68.

Figure 1



Appendix A: Relaxing the assumption (*n*+*d*)=0

Relaxing the assumption $(n+d)=0$ in (2.4) yields:

(A.1) $$\frac{\dot{z}}{z} = sz^{a-1} - \left(n + d + \frac{\dot{A}}{A}\right).$$

We begin with the solution based on the assumption $n+d=0$ and then assess how changes in *n* determine changes in the stationary value of *z*. First, we totally differentiate (A.1) and impose the condition $d\dot{z}/z=0$. We obtain:

(A.2) $$\left[(a-1)sz^{a-2} - aq\ z^{a-1}\right]dz - d(n+d) = 0$$

Now we use the stationary value taken by z for $n+d=0$ in (A.2). By doing so, we obtain the value of the change of $\tilde{z}$ associated with the increase of $n+d$ from zero to $d(n+d)$:

$$\left[(a-1)s\left(\frac{s}{q}\right)^{a-2} - aq\left(\frac{s}{q}\right)^{a-1}\right]dz = d(n+d)$$

$$dz = d(n+d)\left[-s^{a-1}q^{\ 2-a}\right]^{-1}$$

Therefore, $dz<0$ for $d(n+d)>0$. Since we started with $n+d=0$, then $d(n+d)=n+d$. Consequently, we can define the value of $\tilde{z}$ for the case $n+d>0$ as a function of the parameters of the model as follows:

$$\tilde{z} = \frac{s}{q} - \frac{n+d}{s^{a-1} q^{2-a}} \quad .$$

Appendix B: Transitional Dynamics

Log-linearization of equation (3.1) yields:

$$\frac{d \ln y'}{dt} = a \, \frac{d \ln z}{dt} = a \, (a - 1) \tilde{g}^* [\ln z(t) - \ln \tilde{z}] \ ,$$

from which equation (3.2) is obtained. The solution of this differential equation and subsequent passages leading to equation (3.3) are as follows:

$$\ln y'(t_2) - a \ln \tilde{z} = [\ln y'(t_1) - a \ln \tilde{z}] e^{-(1-a)\tilde{g}^* t}$$
$$\ln y'(t_2) - \ln y'(t_1) = \left(1 - e^{-(1-a)\tilde{g}^* t}\right) a \ln \tilde{z} - \left(1 - e^{-(1-a)\tilde{g}^* t}\right) \ln y'(t_1)$$
$$\ln y(t_2) - g_A - \ln y(t_1) = \left(1 - e^{-(1-a)\tilde{g}^* t}\right) a \ln\left(s/q^*\right) - \left(1 - e^{-(1-a)\tilde{g}^* t}\right) \ln y(t_1) + \left(1 - e^{-(1-a)\tilde{g}^* t}\right) \ln A(t_1)$$

where $g_A \equiv \ln A(t_2) - \ln A(t_1)$.

Finally, equation (3.5) is obtained as follows. The general solution of (3.4) is:

$$\ln\left[A^*(t_2)/A(t_2)\right] - \ln \tilde{A} = B(t_1) e^{-\tilde{g}^* t}$$

$$\ln\left[A^*(t_2)/A(t_2)\right] - \ln \tilde{A} = \left\{\ln\left[A^*(t_1)/A(t_1)\right] - \ln \tilde{A}\right\} e^{-\tilde{g}^* t} \ ,$$

$$\ln\left[A^*(t_2)/A(t_2)\right] = e^{-\tilde{g}^* t} \ln\left[A^*(t_1)/A(t_1)\right] + \left(1 - e^{-\tilde{g}^* t}\right) \ln \tilde{A} \ ,$$

$$- \ln A^*(t_2) + \ln A(t_2) = -e^{-\tilde{g}^* t} \ln A^*(t_1) + e^{-\tilde{g}^* t} \ln A(t_1) - \left(1 - e^{-\tilde{g}^* t}\right) \ln \tilde{A} \ ,$$

$$- \ln A^*(t_1) - \tilde{g}^* t + \ln A(t_2) - \ln A(t_1) =$$
$$- e^{-\tilde{g}^* t} \ln A^*(t_1) + e^{-\tilde{g}^* t} \ln A(t_1) - \left(1 - e^{-\tilde{g}^* t}\right) \ln \tilde{A} - \ln A(t_1) \ .$$

Rearranging terms in this latter equation we get (3.5).