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Abstract

We propose a model of growth driven by the co-evolution of institutions and technology. To be consistent with Douglass North (1990, 1991, 1994), institutions are defined as a type of collective knowledge about a specific environment that can prescribe how to adapt general technology before the latter can be actually used. Institutions, then, are treated as a factor in the innovation process, and as such can be purposely accumulated. The simultaneous accumulation of institutions and technology are modeled as an evolutionary game whereby boundedly-rational firms choose how much to allocate to 'institutional spending' vis-a-vis research expenditures, in anticipation of changes in monopoly profits from technological innovation. Using Taylor and Jonker's (1978) Replicator Dynamics to describe the evolution of such strategies, we are able to show how this transition process converges to the steady state model of Romer (1990).

Keywords: endogenous growth, institutions, technological change
JEL: O30, O33, O49, P48, Z13

1 Introduction

This paper analyses economic growth, generally, as the consequence of learning, and specifically, as the result of institutional and technological change. While the notion of knowledge-driven growth (a la Arrow (1962)) may now be commonplace, we identify both institutions and technology as the types of knowledge that matter, and in modeling their evolution, we attempt to reconcile various strands of the growth literature.

One strand, of course, attributes growth to technology. Taking the neoclassical view, (historically large) Solow growth residuals can be explained by exogenous improvements in total factor productivity. And with the seminal

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papers of Romer (1990) and Aghion and Howitt (1992), one may now fully account for persistent growth by endogenising technological change. This is not to say that endogenous growth theory itself is not wrought with problems. While technology has now been established as the 'engine' of long-run growth, inconsistencies still abound. An important question is why the neoclassical growth model seems to be adequate in describing economic performance and cross-country convergence when institutional factors are taken into account.[1] And more generally, why do institutions seem to matter greatly?[2]

The new institutional economics approach to historical economic performance, i.e. Douglass North (1990, 1991, 1994), Davis and North (1991), and North and Thomas (1973), may thus provide a better framework for analysing growth. Yet in spite of the vast empirical literature, Sala-i-Martin (2002) acknowledges that "we are still in the early stages when it comes to incorporating institutions to our growth theories." As expected, there can be numerous approaches to modeling institutional change and growth. First of all, there are many ways of formally defining institutions. Adhering to North, one can relate institutions to transaction costs faced by economic agents, but it is also possible to describe institutions as the overall incentive structure that governs the economy. Acemoglu and Robinson (2000), Benhabib and Rustichini (1996), Vega-Redondo (1993) and Aumann and Kurz (1977), for instance, envisage institutional change as a process whereby the distribution of wealth, or income, is determined.

Secondly, since existing growth models vary, the way in which we depict institutional change may well depend on the specific model we use. Hall and Jones (1999) consider the neoclassical model and argue that institutions (or the 'social infrastructure') affect the productivity of all inputs, while endogenous growth theory may focus on the impact of institutions on the innovation process, as in Kower (2002). Note, however, that while Kower models (financial) institutional change within the Aghion and Howitt quality-ladder framework, a different specification may apply if we treat technological change as horizontal innovations.[3]

Is it institutional development, then, or is it technological change, that drives long-run economic performance? This paper asserts that insofar as knowledge

[1] On the other hand, Mankiw, Romer, and Weil (1992) significantly improves the explanatory power of the neoclassical model by adding human capital as a factor of production, and as shown by Glaeser, et. al. (2004), it may be human capital, and not institutions per se, that cause growth. Interestingly, it may all depend on how one defines, and proxies for, human capital. Note that inasmuch as Lucas (1988) treats human capital as a non-rival good, one may argue that human capital may be equivalent to knowledge/technology, and growth may still ultimately be caused by this.

[2] There is a large empirical literature on the effect of institutions on economic performance. (Durlauf and Quah (1999) list over 80 notable papers. For an annotated bibliography by the World Bank of the effect of governance on development, see http://www1.worldbank.org/publicsector/anticorrupt/annotatedbibliography.pdf.) Some well-known studies include Sala-i-Martin (1997), Knack and Keefer (1995), Mauro (1995), Hall and Jones (1999), and more recently, Acemoglu et al. (2002, 2001), Easterly and Levine (2003), and Rodrik et. al (2004).

[3] See, then, section 2 for such specification within the Romer model.

is the prime determinant of growth, then technologies, in the form of research and innovation, and institutions, corresponding to 'social' knowledge, both influence growth and development. Although the recognition of institutions as the product of social learning or a type of 'collective' knowledge can already be seen in North, influential work by Nelson and Winter (1982) and, more recently, Nelson (2002) which model growth as an evolutionary process treat institutions as 'social' technologies or routines that develop through time as a result of the combined forces of mutation, selection and inheritance.[4]

Nelson further argues for the 'co-evolution', or the interdependence of institutional and technological change, using as historical illustrations the two-way causality between innovation and institutions in the rise of mass production in the US and in the development of a science-based industry in Germany.[5] North himself provides historical examples which show how institutional developments have increased incentives to production and innovation (as in the industrial evolution, which was made possible because of the creation of institutions that protected intellectual property rights). But the causation need not always have been unidirectional. For instance, North (1991) illustrates how, throughout history, expansions of markets and long-distance trade (which arguably have been made possible by underlying technological improvements) have led to institutional developments to overcome transaction costs.

A comprehensive and unified treatment of economic growth would thus entail modeling the co-evolution of institutions and technology. Vega-Redondo (1993) develops such a model but which, although more formal than Nelson, is too schematic. Instead, this paper offers a more defined, empirically testable, approach that endogenises institutional and technological change and traces corresponding growth rates during transition towards, and at, the steady state.[6]

Thus, in the next section, we take Romer as our point of departure and analyse the steady state (where the quality, but not the 'quantity', of institutions is treated as fixed) and show that the balanced growth rate depends on a constant rate of diffusion and adaptation of technology, which in turn is influenced by the quality of institutions. With perfectly effective institutions, the model reverts to the original results in Romer; otherwise, growth in the steady state is relatively slower.

Section 3 provides the more novel and larger part of the paper in modeling the transition dynamics along which institutional quality itself co-evolves with technological quality. We show how shocks to the steady state trigger an evolutionary game that generates an endogenous change in institutional and technological quality. In doing so, we formalise the mechanism envisaged by North in which institutions develop as an adaptive response to, and to reduce the uncertainty in, the new climate.

We assume that, generally, the way relevant shocks affect quality is by al-

[4] Dosi and Nelson (1994) provide a survey of evolutionary modeling in economics.

[5] Fagerberg and Verspagen (2002) also recognise the mutual dependence of technological and institutional change (also within an evolutionary framework).

[6] We do not (yet) provide empirical results here, but Desierto (2005) presents some hypothetical simulations.

tering the anticipated interest cost of the firm. The interest cost is here interpreted as the effective cost of financing a technological innovation, incorporating all transaction costs faced by firms.[7] We argue that when the shock can (still) be anticipated, there can be some uncertainty in the aggregate economy as to the 'correct' interest cost, and hence, uncertainty as to the level of profits that can be maintained. This allows each firm to react to the shock by adopting either of the following two anticipatory moves: it can spend on institutional development, thereby creating external effects for the whole economy - institutions being public goods; or it can adjust the price of its own product, thereby aiming to fully capture the excludable benefits. As expected, the second alternative yields relatively higher profits. However, the first alternative is a 'safer' option.[8] This is because an increase (decrease) in a firm's level of profits implies a decrease (increase) in the wages it pays to its human capital. If the firm's set of human capital is perfectly mobile, it can move out of the firm if wages are decreased, leaving the firm with zero profits. However, if human capital has some uncertainty or adjustment costs, it cannot readily move out, and the firm can capture the relatively higher profits at a lower wage. Choosing the first strategy, on the other hand, guarantees that the relatively lower profit is actually obtained, since in this case, human capital has no reason to move out of the firm.

Within the context of evolutionary games, this uncertainty is translated into the assumption of bounded rationality, which implies that firms and their human capital cannot simultaneously predict each other's preferred strategy on wages or profits (nor the corresponding strategy on institutional spending and product price). They instead play a coordination game, repeatedly and continuously, until the 'correct' or 'stable' strategy is learned in the aggregate, and the new steady state is asymptotically reached. To describe such evolution of strategies, we use Taylor and Jonker's (1978) Replicator Dynamics .

Finally, section 4 provides a brief intuitive interpretation of the proposed co-evolutionary model of growth, while section 5 concludes.

2 The Steady State

For ease of exposition, we first describe the steady state, i.e. the limit case to which the transition dynamic in section 3 converges. It is straightforward to adjust the Romer (1990) model in order to accommodate institutional change if we explicitly define institutions as a type of knowledge which is country, or environment, specific.[9] Romer defines knowledge as "instructions for working

[7] Kower, also using North's concept of institutional change, shows the link between transaction costs, financial-sector development, and innovation. Our approach, however, is not necessarily confined to financial institutions.

[8] That is, the first strategy is 'risk-dominant' in a game-theoretic sense. See Harsanyi and Selten (1988).

[9] "Institutions are the external mechanisms individuals create to structure and order the environment" (North (1994)). Although Nelson (2002) dubs institutions as "social technologies", we make a more explicit specification in confining these technologies to specific countries

with raw materials". In the same manner, we could argue that institutions, as long as they are "humanly devised constraints that structure human interaction" (North 1994), could be thought of as sets of instructions that, when used in the production of technology, would help prescribe the production process. The extent of their relevance in technology-creation could be captured by a parameter that describes the quality, or level of effectiveness, of institutions.

North's concept of institutions can then be incorporated in the Romer model if we specify that each blueprint (which represents a particular technology) has a portion of knowledge, or 'instructions', that is general and a portion that is (country) specific. The latter would be of importance whenever the (country-specific) environment is relevant to technology creation. The environment in this case could be thought of as an additional 'raw material' that might be relevant because the technology might need to be adapted to the environment before it could be used. Hence, given a specific environment, each blueprint might need to have not only a portion allocated to 'general' production instructions, but also to the adaptation process, which we dub 'specific' knowledge.

To describe the evolution of technology, A, in the steady state, we modify the Romer model as follows:

$$\dot{A} = \delta H_A I^{\gamma} A_g^{1-\gamma}, 0 \leq \gamma \leq 1, \tag{1}$$

where H_A is human capital employed in research, δ is a fixed productivity parameter, $A_g$is general knowledge, I is institutions defined by $I = \frac{A_s}{E}$, and A_s is the specific knowledge about the corresponding specific environment $E > 1$. Therefore, we can rewrite (1) as $\dot{A} = \delta H_A \left(\frac{A_s}{E}\right)^{\gamma} A_g^{1-\gamma} = \frac{\delta H_A A}{E^{\gamma}}$, since, within that particular environment, all knowledge is shared or diffused, i.e. $A_s = A_g$.[10]

In another paper (see ch. 4 of Desierto (2005)), we have specifically measured E as the volume of the (three-dimensional) geographical space in which all firms are located. However, here we suggest that the conceptual definition of E may include other exogenous variables that may affect the diffusion of technology, so that E need not only refer to geography, but can also include the underlying *exogenous* cultural, political and social environment.[11] Such variables can refer to what Davis and North (1971) define as the 'institutional superstructure'. (Including this exogenous institutional climate may thus require an increase in the dimension of 'location' of firms beyond three.)

The measurement of an economy's aggregate E may also reflect the intuition that a more homogeneous environment is 'smaller'.[12] That is, a more uniform

or environments. This would be useful in an open economy setting, for we may now be able to explain why not all knowledge can readily spill over across countries. (Desierto (2005) provides an open-economy interpretation of the model.)

[10] It is assumed that a country has one specific environment which all firms share, but the analysis can easily accommodate heterogeneity within a country by treating particular environments as separate economies.

[11] Although the extent of exogeneity and possible endogeneity may be a matter of contention, language, religion, some norms and values, the constitution, and basic laws ingrained therein such as property rights may arguably provide some examples.

[12] One could think that greater clustering (in space and institutional environment) of firms in an economy would translate to smaller aggregate E.

permeation of the aggregate geography and institutional superstructure among firms within the economy can probably be reflected as smaller aggregate environment E, in which it is inherently easier for a certain technology to be applied and diffused, all things being equal. Such a treatment could be made consistent with the literature on the new economic geography and the spatial economy.[13] A major difference here is that 'space' (geography and institutional superstructure) can be overcome by the value of γ. Particularly, with $\gamma = 0$, it does not matter at all how large or complex the environment is. It can be seen in this case that the environment (and institutions I) would have no influence in the production of technology, and the model would revert to the original Romer specification, i.e. $\dot{A} = \delta H_A A$, where the evolution of technology would be relatively faster.[14]

We thus interpret γ as the quality, or level of effectiveness, of (the relevant set of) institutions. Indeed, the parameter γ could be interpreted as the 'factor' intensity of institutions I, or environment E, in knowledge creation. The lower γ is, the more effective the current set of institutions would be, thereby rendering further production of A_s, for adaptation of A_g, unnecessary. When $\gamma = 0$, innovations would be readily usable, and effective institutions could be interpreted as pure public goods that are completely non-excludable. Such 'perfect' institutions would already be 'subsumed' in (the skills) of human capital inasmuch as all human capital have full, equal access, to pure public institutions. Whenever $\gamma > 0$, there would still be relevant institutions that are not yet effective or purely 'public', which might then provide the incentive for further endogenous accumulation of institutions by producing specific knowledge A_s (alongside general knowledge A_g). Thus, γ could capture the extent to which the adaptation process (increases in A_s) could be excluded from every new blueprint that is produced.

We can easily solve for the balanced growth rate as in Romer, while incorporating the role of institutions. However, instead of economy j being composed of separate research, durable-good, and manufacturing sectors, we assume that researchers are directly hired by the (durable good) firms, so that the price of the blueprints that researchers produce is seen as an internal price.[15] The monopolistically-competitive firms produce durable goods according to the corresponding blueprints produced by their researchers, which are then supplied to a single manufacturing sector that produces output according to a modified Cobb-Douglas production function:[16]

[13] For a survey of the literature, see, for example, Fujita, Krugman, and Venables (1999) and Ottaviano and Thisse (2003). Note that space in our model does not only refer to geographical characteristics but to the institutional superstructure as well.

[14] Of course, it is possible to re-interpret Romer's productivity parameter as $\delta = \frac{1}{E^{\gamma}}$, although in this case we would be disregarding other factors that could potentially affect the productivity parameter.

[15] Note that Romer mentions the possibility of using this alternative setup without affecting the results of the model. More importantly, it conveniently allows us to visualise the evolutionary game in section 3 as a pair-wise game played between a durable-good firm and its own set of researchers.

[16] We follow Romer's notation wherever possible.

$$Y_j = H_{Y_j}^{\alpha} L_j^{\beta} \int_0^{A_j} x_j(i)^{1-\alpha-\beta} = H_{Y_j}^{\alpha} L_j^{\beta} A_j x_j^{1-\alpha-\beta}, \tag{2}$$

where aggregate final output, Y_j, is produced by the total human capital employed in the manufacturing sector H_{Y_j}, and labour L_j, from the entire set of durable goods, each supplied at the level x_j, the variety of which are determined by the blueprints A_j that have already been produced by researchers.[17] (With $K_j = \eta A_j x_j$, that is, capital K equal to η units of foregone consumption needed to produce the total durable goods required in production, output can also be expressed as $Y_j = \left(H_{Y_j} A_j\right)^{\alpha} \left(L_j A_j\right)^{\beta} K_j^{1-\alpha-\beta} \eta^{\alpha+\beta-1}$.) Recalling equation (1), knowledge (measured as blueprints) is produced by researchers H_{A_j} according to:

$$\dot{A}_j = \delta H_{A_j} I_j^{\gamma} A_{g_j}^{1-\gamma} = \frac{\delta H_{A_j} A_j}{E_j^{\gamma_j}}, \tag{1a}$$

where $0 \leq \gamma \leq 1$, and $I = \frac{A_s}{E}$, so that $\dot{A} = \delta H_A \left(\frac{A_s}{E}\right)^{\gamma} A_g^{1-\gamma} = \frac{\delta H_A A}{E^{\gamma}}$, since in a closed economy all knowledge is diffused, i.e. $A_s = A_g$.

All income in research goes to human capital researchers, H_{A_j}, however, their wage rate, $W_{H_{A_j}}$, is now limited by their environment, E_j, and the effectiveness of institutions, γ_j. That is,

$$W_{H_{A_j}} = \frac{\delta P_{A_j} A_j}{E_j^{\gamma_j}}, \tag{3}$$

where P_{A_j} is the price of the blueprint.

The demand of the final output sector for durable goods is obtained by maximizing profit conditional on x_j, after the scale of operation and the levels of L_j and H_{Y_j} have been determined, implying:

$$p_j(i) = (1-\alpha-\beta) H_{Y_j}^{\alpha} L_j^{\beta} x_j(i)^{-\alpha-\beta}. \tag{4}$$

Note that the durable-good sector is monopolistically competitive.[18] Each firm incurs a fixed cost for the blueprint and obtains a monopoly over its use in durable-good production.[19] It chooses the level of x_j that maximizes revenue, $p_j(x_j) \cdot x_j$, minus variable cost, $r_j \eta x_j$, where r_j is the interest rate, and ηx_j are the total units of output (or foregone consumption) used in the production of durable goods. By use of equation (4), the monopoly-pricing problem reduces to:

[17] Although this paper strictly pertains to a closed economy, for tractability, we assume that some values would be the same across economies in an open economy framework (see Desierto (2005)), and thus for these parameters we omit the subscript j.

[18] Although firms earn a stream of (positive) profits, with free entry, "firms earn zero profit in a present value sense." (Romer 1990). That is, the present value of the stream of profits goes to the purchase of blueprints. See equation (8).

[19] Its monopoly is only in terms of production. Knowledge is non-rival, so that it can be used universally in research, but non-owners of the blueprint are excluded from using it to produce the corresponding durable good (Romer 1990).

$$\pi_j = \max_{x_j} p(x_j)\, x_j - r_j \eta x_j = \max_{x_j} (1-\alpha-\beta)\, H_{Y_j}^{\alpha} L_j^{\beta} x_j (i)^{1-\alpha-\beta} - r_j \eta x_j. \quad (5)$$

The price of durable goods is thus a mark-up over marginal cost:

$$p_j = \frac{r_j \eta}{1-\alpha-\beta}, \quad (6)$$

which, when substituted into the demand equation (4) can solve for the level of durable goods supplied to the final goods sector:[20]

$$x_j = \left[\frac{(1-\alpha-\beta)^2 H_{Y_j}^{\alpha} L_j^{\beta}}{r_j \eta}\right]^{\frac{1}{\alpha+\beta}}. \quad (7)$$

Equilibrium profit is thus $\pi_j = (\alpha+\beta)\, p_j x_j$. The fixed cost of the blueprint incurred by the durable goods firm is recouped through a stream of rental payments from the final output sector. Thus, the price of the blueprint, P_{A_j}, is bid up by durable goods producers until it equals the present value of durable-good sector profits, $\frac{\pi_j}{r_j} = P_{A_j}$, so that:

$$P_{A_j} = \frac{(\alpha+\beta)\, p_j x_j}{r_j} = \frac{(\alpha+\beta)(1-\alpha-\beta)\, H_{Y_j}^{\alpha} L_j^{\beta} x_j^{1-\alpha-\beta}}{r_j}. \quad (8)$$

Since human capital is employed either in research or in manufacturing, $H_j = H_{Y_j} + H_{A_j}$, the wage rate of researchers equals the marginal productivity of human capital in the final output sector:

$$\frac{\delta P_{A_j} A_j}{E_j^{\gamma_j}} = \alpha H_{Y_j}^{\alpha-1} L_j^{\beta} A_j x_j^{1-\alpha-\beta}. \quad (9)$$

Using equations (8) and (9), we can thus solve for the level of human capital in manufacturing:

$$H_{Y_j} = \frac{E_j^{\gamma_j} \alpha r_j}{\delta (1-\alpha-\beta)(\alpha+\beta)}. \quad (10)$$

To close the model, Romer uses the following consumers' intertemporal utility function with constant elasticity of intertemporal substitution, $\frac{1}{\sigma}$:

$$\int_0^{\infty} U(C)\, e^{-\rho t} dt, U(C) = \frac{C^{1-\sigma}-1}{1-\sigma}, \sigma \in [0, \infty), \quad (11)$$

[20]"Because of the symmetry in the model, all the durable goods that are available are supplied at the same level (henceforth denoted as x). If they were not, it would be possible to increase profits in the producer durable sector by reducing the output of high-output firms and diverting capital released in this way to low-output goods" (Romer 1990). While in the steady state, the level x is the same for all firms, the transition dynamics in section 3 makes explicit the process of adjustment towards a single level of x and the equalization of profits of all firms.

with ρ as the preference parameter. With a fixed r_j, the optimizing condition for consumers is thus:

$$\frac{\dot{C}_j}{C_j} = \frac{r_j - \rho}{\sigma}. \tag{12}$$

With H_{Y_j}, L_j and x_j fixed in the steady state, it can be seen from equation (2) that output Y_j would have to be growing at the same rate as knowledge, equal to $\frac{\dot{A}_j}{A_j}$. Capital K_j also grows at the same rate as Y_j, since η and x_j are fixed, and with $\frac{K_j}{Y_j}$ constant, consumption grows at the same rate as capital.[21] Thus, in equilibrium, all the variables grow at a constant exponential rate:[22]

$$\frac{\dot{K}_j}{K_j} = \frac{\dot{Y}_j}{Y_j} = \frac{\dot{C}_j}{C_j} = \frac{\dot{A}_j}{A_j} = \frac{\delta H_{A_j}}{E_j^{\gamma_j}}. \tag{13}$$

Given the constraint $H_j = H_{Y_j} + H_{A_j}$,and using equation (10), the growth rate, $g_j = \frac{\delta H_{A_j}}{E_j^{\gamma_j}}$,is thus equal to:

$$g_j = \frac{\delta H_j}{E_j^{\gamma_j}} - \Lambda r_j, \text{where } \Lambda = \frac{\alpha}{(1-\alpha-\beta)(\alpha+\beta)}, \tag{14}$$

which, with equation (12), can be expressed in terms of the economy's fundamentals:

$$g_j = \left(\frac{\delta H_j}{E_j^{\gamma_j}} - \Lambda\rho\right)\left(\frac{1}{\sigma\Lambda+1}\right). \tag{15}$$

Equations (14) and (15) are the counterparts of the equilibrium growth rate in the Romer model when the latter is adjusted for the effect of the environment E and the effectiveness γ of institutions.[23] Note that in limit case where institutions are perfectly effective, i.e. $\gamma = 0$, the economy grows according to Romer's model, but whenever $\gamma > 0$ growth is relatively smaller. The exogenously given E and steady-state level $\gamma > 0$ act to limit the productivity of human capital in research, and thus can curtail the otherwise larger growth rate implied in Romer.

Additional insight on the role of institutions can be gained by studying the expression for equilibrium wages of human capital (derived as equation (3)), i.e.

$$W_{H_A} = \frac{\delta P_A A}{E^{\gamma}},$$

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[21] Capital is accumulated as foregone output: $\dot{K}(t) = Y(t) - C(t)$. Thus, $\frac{C}{Y} = 1 - \frac{\dot{K}}{Y} = 1 - \frac{\dot{K}}{K}\left(\frac{K}{Y}\right)$.

[22] They grow exponentially since A is linear in A, and at a constant rate since H_A stays constant in equilibrium (Romer 1990).

[23] In Romer's model, $g = \delta H - \Lambda r$ and in terms of fundamentals, $g = \frac{\delta H - \Lambda\rho}{\sigma\Lambda+1}$.

where P_A is the price of the innovation, equal to the present value profit $\frac{\pi}{r_j}$. The expression above implies that with a higher γ, wages of H_A are lower. Following Hall and Jones (1999), this suggests that with less effective institutions (higher γ), the foregone wage of human capital is spent on diversion activities to capture the (entire) profit from A, instead of producing only general technology.

Thus, the entire 'institutional effect', can be formally captured by $\left(\frac{A_s}{E}\right)^{\gamma}$. Such a definition can encompass a wide range of institutions, both formal and informal. Financial institutions, governance including laws and courts (especially patent laws and enforcement), cultural traits (including language), and informal organisations that embody social capital have all been believed to affect growth.[24] Since institutional factors can potentially affect the whole process of technology production and diffusion, from making available existing knowledge for further research up to producing the corresponding durable sector for use in the final output sector, there can thus be some motivation for deliberate 'institutional spending' by firms. That is, firms can spend not only on research, but also on lobbying, litigation, organizational changes, the development of financial instruments and accounting techniques, and even advertisement, all of which help change the existing body of formal and informal institutions in the hope of maximizing the profits that can be obtained from technological innovation.

Think of an economy that starts from a steady state in which γ is fixed. That is, the amount of 'effort' spent by firms towards institutional change (vis-à-vis towards 'general' knowledge production) is just enough to keep the level of aggregate institutional quality. Additions to the current body of institutions, in the form of A_s, have to be made by the firm if it wants to produce a particular blueprint, but it does so by spending, or 'diverting' from human capital wages, an amount dictated by the fixed γ. Note that although the set of institutions becomes larger or complex with each new technology that is created, the aggregate 'quality' of institutions remains the same, thereby keeping profit and productivity of all other firms unaffected. That is, the difference between additions to A_s and possible changes in γ is that the latter affects the profits of all firms, while the effects of the former apply only to a particular firm or technology.[25]

In the next section, we see how γ evolves to approach its steady state level, but before proceeding to the transition dynamics, note that while A_s and γ

[24] For recent surveys and studies, see, for instance, Kower (2002) on the role of financial development, and Durlauf and Fafchamps (2004) on social capital. Mauro (1995) and Hall and Jones (1999) use political indicators, with the latter also including geographical and cultural variables. Sala-i-Martin (1997) runs regressions on combinations of various institutional factors. Boulhol (2004) uses a new institutional database developed by the French Ministry of Economy, Finance and Industry that covers 115 indicators.

[25] For instance, software firms might push for anti-piracy laws, but this bears no direct relevance to the biotech industry; or the latter can spend on advertising to influence public attitude towards genetic cloning, but this has no use for the IT industry. Such efforts add on to the existing body of institutions (laws and culture, in this instance) without influencing aggregate institutional quality. That is, each innovation increases the aggregate cost of institutions, albeit the percentage of institutional spending per innovation remains fixed. Section 3 considers institutional changes that have wider-reaching effects by allowing γ to evolve endogenously.

may evolve endogenously, E is exogenous, i.e., outside of firms' scope of influence.[26] Shocks to E are always unanticipated. If a shock can be anticipated, then arguably, firms can treat them as anticipated changes in the interest rate, and can thus initiate changes in γ to (at least) keep profits from decreasing.[27] That is, a transitional dynamic can be triggered, in which the interest rate and institutional quality are the variables that evolve, rather than the environment.

3 Transition Dynamics

We can note from equation (4) in the preceding section that durable-good firms share the same demand from the final-output sector. Since these firms also face the same interest cost, they earn the same level of durable-good firm profits, and supply the same level of durable good, x. Also, given the same r, E, and H_Y, faced by all firms and both sectors (manufacturing and durable-good/research), it must follow that γ is fixed, so that wages within and across sectors remain equal. In the transitional dynamics we are about to discuss here, we are not only able to characterise the evolution of the interest rate cost, r (and hence the level of durable goods, x) towards its equilibrium value, but we are also able to show the simultaneous evolution of γ towards its steady state level. Anticipated changes in the interest cost are treated as shocks that trigger the endogenous evolution of γ in which the adoption of a particular strategy for γ reveals the true transaction cost and hence, the stable level of profits, which in turn determines the stable strategy for γ. The Replicator Dynamics (RD) in section 3.2 describe such adjustments in the level of institutional quality, and transaction costs and profits, as firms start preparing for the anticipated change in the interest cost. The framework is based on the strategic behaviour of boundedly-rational firms that continuously play a (evolutionary) game to eventually determine the stable level of γ, the structure of which is outlined in the following section 3.1.

3.1 Strategic Behaviour

From equations (8) and (9), we can obtain a function for γ that equates the marginal productivity of H_{Y_j} with the wage rate of H_{A_j}:

$$\gamma_j = \frac{\log\left[\delta\left(\alpha+\beta\right)\left(1-\alpha-\beta\right)H_{Y_j}\right] - \log \alpha r_j}{\log E_j}. \tag{16}$$

At the steady state, γ is a 'convention'.[28] A relevant shock to the steady state, which can change the interest cost r, may make γ unstable and thus evolve potentially to another level. However, this does not necessarily provide a

[26] E, like γ, is fixed in the steady state, but while γ may evolve out of the steady state, E is always treated here as an exogenous variable.

[27] See section 3.

[28] Young (1993) defines a convention as a "pattern of behaviour that is customary, expected and self-enforcing." A convention is evolutionarily stable. Thus, the steady state γ, being a fixed level, is evolutionarily stable.

motivation for a change in γ. It can be seen from equation (16) that for a given E_j, a change in r_j can lead to a change in γ_j only if H_{Y_j} does not change to the extent of fully offsetting the change in r_j. An exogenous decrease in r_j, at the current level of profits, increases P_{A_j}, which increases the income per blueprint of researchers (provided γ does not increase to offset it), and thus prompts a movement of human capital from manufacturing to research. The new level of H_{Y_j} can be easily computed from equation (10) by replacing r_j with a new level. However, if H_{Y_j} is to remain fixed, given a change in r, then γ_j can change, but for this to happen adjustment costs that hamper the mobility of human capital must be in place.

Before defining the particular assumptions on mobility, note that there is a crucial strategic element that comes from assuming that there is a fixed total amount of human capital that is allocated between sectors, i.e. $H_j = H_{Y_j} + H_{A_j}$, and a fixed amount per firm in the durable-good sector, i.e. $H_{A_i} = \frac{H_{A_j}}{N_j}$, where N_j is the number of firms in the economy. The profits that each firm actually obtains not only depends on the demand it faces (which depends on H_{Y_j}), but is also contingent on its staying 'operative' or, equivalently, since a firm undertakes both research and durable-good production, on whether or not it can maintain its $H_{A_i} = \frac{H_{A_j}}{N_j}$.[29] Thus, since the level of γ that each firm chooses affects the wage it pays to its own researchers, the choice of γ potentially prompts some (inter and intra-sector) movement of human capital, which ultimately affects the profits that the firm actually obtains. However, due to the assumption of bounded rationality, individual firms cannot know beforehand other firms' strategies for γ (and hence their wage) and, thus, cannot predict the exact extent of human capital mobility. Therefore, firms play a continuous game to eventually 'learn' the 'correct' strategy for γ and a wage that reflects the true marginal productivity of human capital, i.e., the strategy that prevents further movement of human capital.

3.1.1 Assumptions

We now clarify the assumptions upon which the payoffs of the game are based. First, in this out-of-steady-state version of the model, there is asymmetry in the mobility of human capital based on heterogeneous adjustment costs. Particularly, we assume that inter-sector relocation of human capital is more costly than intra-sector movement. This may be indicative of some inherent differences between the skills required in manufacturing and in the durable-good sector, highlighted during periods of transition, which make H_Y and H_A imperfect substitutes. For instance, H_Y could pertain to high-level managerial skills, rather than to innovation performed by scientists and engineers.

[29] In this setup where the researchers are explicitly employed in the durable-good firm, it is now as if the patent for the blueprint is owned by its researchers. That is, the firm pays itself the value of the blueprint (and hence, uses an internal price P_A) to be able to produce the corresponding durable good. If the firm loses its researchers, it loses its patent, or its right to produce the durable good and hence the profits associated with it.

Thus, suppose for a given maximum wage $w_{\max}$ and a minimum wage $w_{\min}$, H_Y can start moving into research (and/or H_{A_i} can move into manufacturing) only if it can obtain $w > w_{\max}$, while H_{A_i} can immediately and completely move out of its current firm to another research/durable-good firm if it can earn $w > w_{\min}$. There may be heterogeneity among firms as well, so that by moving out of its current firm but still staying in research, H_{A_i} can earn potentially any amount from the range $(w_{\min}, w_{\max}]$. This heterogeneity in the research/durable good sector is not responsible for triggering the dynamics per se, but what is essential is that the cost of inter-sector movement is greater than $w_{\max}$, while the cost of intra-sector relocation is at most $w_{\max}$.[30]

Within this framework, the relevant shocks that can initiate the dynamics can thus be 'anticipated', thereby allowing firms to 'prepare' for any impending change in the interest cost by adjusting the level of γ, ahead of any response from the manufacturing sector in the form of inter-sectoral movement of human capital.[31]

The next two assumptions - bounded rationality and a large number of firms- are to some extent related to the assumed asymmetry of human capital mobility. Bounded rationality is captured by the feature that firms cannot predict whether, and/or by how much, all other 'players' respond to the shock which, in effect, reflects some uncertainty as to the 'correct' strategy for γ. This assumption can be justified if there is asymmetry of adjustment costs or heterogeneity of firms. If, instead, all firms were the same, then the correct strategy is easily predicted. That is, if there were, first of all, no inter-sector asymmetry, there would be no opportunity for research/durable good firms to 'anticipate' shocks ahead of the manufacturing sector by changing γ in response to a change in r, but instead, H_Y decreases or increases to reflect the new productivity of all human capital. (Recall from equation 16 that the proportional adjustment of r and H_Y 'prevents' changes in γ.) Thus, in this case, it is as if the strategy for γ is easily 'predicted', i.e. as if there is no bounded rationality with respect to this, inasmuch as γ remains at the same level prior to the shock.

Secondly, if there were (strictly) no intra-sector asymmetry, but as long as there is some inter-sector heterogeneity, γ could still change, but in this case, the new level of γ could be easily predicted, or 'solved for', given the new 'predictable' level of H_Y. That is, if the entire research sector could predict how H_A, and consequently H_Y, would change, then this sector could play a one-

[30] Intra-sector adjustments only influence the speed of adjustment during transition. In simulations performed in Desierto (2005), we illustrate that the more homogeneous the research/durable sector, the faster the dynamics approach the steady state.

[31] A prime example of such a shock is integration to global/regional markets. Firms have the opportunity of adjusting human capital productivity by changing γ even before the global/regional interest cost is adopted, i.e. while the domestic economy is still strictly closed, if the firms anticipate eventual integration. See Desierto (2005a) for the specific model. Other examples could be the threat of war or revolutions and impending political regime changes or constitutional amendments. Strictly, what firms are anticipating is a change in interest rate, so that even 'unanticipated' shocks, i.e. natural calamities and disasters, could translate into an 'anticipated' interest rate change. In this paper, however, we use the term 'anticipated shock' to mean 'anticipated interest rate change'.

shot game to determine the strategy for γ that would reflect the true difference in inter-sectoral human capital productivity. It is then as if there could be no (or only very little) bounded rationality within the research/durable good sector, which could weaken the justification for using a repeated and continuous (evolutionary) game to model the evolution of γ. Thus, independent of the assumption of human capital heterogeneity or asymmetry, which after all could be due to some inherent differences of human capital, we explicitly assume bounded rationality across sectors and among research/durable good firms.[32]

Lastly, assuming a large population of firms reinforces the asymmetry in the responses, and the associated bounded rationality, of firms, as it becomes less plausible that the research/durable-good sector remains homogeneous, and 'boundlessly' rational so as to be incapable of making mistakes, the larger the number of firms within that sector.[33] Taken together and applied to our particular model, these assumptions allow us to characterise the transition dynamics as a repeated and continuous (evolutionary) game driven by uncertainty, and, thus, as a learning process by which the steady state is eventually reached.

3.1.2 Evolutionary Game

The general evolutionary game used in the dynamics is characterised by firm-players that are continuously and 'randomly drawn' to play a pair-wise game, whose strategies are particular values of γ which yield associated payoffs that depend on the strategy of the firm's 'random pair'. The 'pair' can be seen to represent the strategy of a firm i, and the preferred strategy of its own human capital, H_{A_i}, so that the game becomes a matching of strategies of the firm with its current H_{A_i}.[34] Similarly, it could be interpreted as the matching of an original strategy and a revised strategy, that is, the strategies that are adopted before and after the true adjustment cost of H_{A_i} is known.[35] The pairing is 'random' since the true adjustment cost is not known at the time the original strategy is implemented, i.e. the researchers (if they own the firm) may validate the original strategy or revise it at random to reflect their true adjustment cost. Thus, at each (continuous) 'draw', it is as if a firm does not know with whom it is paired.

From equation (3), it follows that, given the price of blueprints, a change in γ changes the wage that researchers obtain per blueprint.[36] Suppose that there

[32] Bounded rationality as to the correct strategy for γ necessarily implies, or is translated into, some amount of heterogeneity of firms and human capital. Arguably, asymmetric adjustment costs are not always attributable to, but can justify, bounded rationality.

[33] We also assume a large population in order to use the deterministic Replicator Dynamics that relies on the law of large numbers in treating the average fitness of strategies as expected payoffs. See Boylan (1992, 1995) for an analysis.

[34] Thus, if N_j is the actual number of firms, the number of (firm-)players is $n_j = 2N_j$.

[35] This latter interpretation may be more useful if we explicitly assume that each firm is owned by its researchers.

[36] Note that as researchers produce more blueprints, the income or wage per researcher increases. Thus, wage rates of researchers, and the marginal productivity of H_Y increases

are pre-determined values for the maximum and minimum wages per blueprint, and that each strategy for γ corresponds to a particular wage, then the following game, which is based on the assumed asymmetric mobility of human capital, illustrates the different alternatives that a firm might consider:

	$w_{\max}$	$w > w_{\max}$	$w_{\min} < w_{\max}$
$w_{\max}$	$\pi_{\min}, \pi_{\min}$	π_C, π_C	$\pi_{\min}, 0$
$w > w_{\max}$	π_C, π_C	π_A, π_A	$\pi_B, 0$
$w_{\min} < w_{\max}$	$0, \pi_{\min}$	$0, \pi_B$	$\pi_{\max}, \pi_{\max}$

where $\pi_A < \pi_B \lesseqgtr \pi_C < \pi_{\min} < \pi_{\max}$.

Given the interest cost r, the environment E, institutional quality γ, and the level H_Y of human capital in manufacturing, we can obtain a reduced form equation for firm profit by using equations (6), (7), and (10) and the fact that equilibrium profits are $\pi_j = (\alpha + \beta)\, p_j x_j$. That is,

$$\pi = \zeta r^{\frac{2\alpha+\beta-1}{\alpha+\beta}} \left(E^{\gamma}\right)^{\frac{\alpha}{\alpha+\beta}}, \tag{17}$$

where $\zeta = \frac{\alpha^{\frac{\alpha}{\alpha+\beta}} (1-\alpha-\beta)^{\frac{2-2\alpha-\beta}{\alpha+\beta}} [L(\alpha+\beta)]^{\frac{\beta}{\alpha+\beta}}}{\delta^{\frac{\alpha}{\alpha+\beta}} \eta^{\frac{1-\alpha-\beta}{\alpha+\beta}}}$. We assume that $\alpha > \frac{1-\beta}{2}$ so that the interest cost positively affects profit.[37]

Thus, different levels of γ (corresponding to different wages) can yield different levels of profit. Note, however, that wage strategies need not match or, alternatively, original strategies may be (randomly) revised. That is, either the firm can over-or-underestimate the productivity of its human capital or, in the alternative scenario where the firm is owned by its researchers, the latter can pre-commit to a level of productivity that they find they cannot achieve. The failure to match strategies may then lead to movement of human capital out of its current firm and a re-organisation into a new firm (if productivity has been underestimated), or attract additional human capital into the current firm (if productivity has been overestimated). This has implications on the actual profit that the firm obtains. Firstly, if any resulting transfer of human capital involves inter-sector movement, the actual levels of H_Y may be different from the 'pre-calculated' level used in the original formulation of equation (17) . Secondly, earning any level of profit in the first place depends on whether or not that particular firm remains operative, i.e. if it (still) has the blueprint necessary to produce the durable good. Thus, the above game yields the same level of profits for strategies that match since in this case there is no incentive for human capital movement.

with A even at the steady state. What prompts the movement of human capital is not the change in wage rates per se, but the change in the wage rate or marginal productivity per blueprint, which, ceteris paribus, changes when γ changes.

[37] Subscript j has been ignored not only to lighten the notation but, more importantly, so that equation (17) can easily be used to calculate alternative profit levels using different values for the variables.

The maximum wage $w_{\max}$, when matched with itself, yields the corresponding profit minimum, $\pi_{\min}$, while the pair $(w_{\min}, w_{\min})$ yields $\pi_{\max}$. From equations (3) and (17), note that wage per blueprint is negatively related to γ, while profit is positively related to γ. A 'minimum' γ can thus be associated with $w_{\max}$ that can yield $\pi_{\min}$, while a 'maximum' γ can imply $w_{\min}$ that can obtain $\pi_{\max}$.

The ordering of payoffs as $\pi_A < \pi_B \lesseqgtr \pi_C < \pi_{\min} < \pi_{\max}$ is based on the assumed asymmetry of human capital. Generally, H_Y is relatively less mobile than H_A, but the latter tends to stay in research should it move out of its present firm. Recall that H_Y can only start moving to the research sector when a firm offers $w > w_{\max}$, while H_{A_i} moves completely out of its firm if it can earn $w > w_{\min}$. Of course, there is no need for H_{A_i} to move if it already earns $w > w_{\min}$ in its current firm. In this case, H_{A_i} moves out if it can earn an even higher wage.

Thus, if firm i is prepared to pay its H_{A_i} a level of wage per blueprint equal to $w_{\max}$, and the true productivity per blueprint of H_{A_i} is also $w_{\max}$, then H_Y does not move to the firm, nor does H_{A_i} move out of the firm. The firm earns $\pi_{\min}$, and the 'compatible' profit for H_{A_i} is also $\pi_{\min}$. If both firm i and its H_{A_i} 'adopt' the same strategy $w_{\min}$, then H_Y and H_{A_i} also remain where they are, and the symmetric payoff is $\pi_{\max}$.

If a (symmetric) level $w > w_{\max}$ is adopted, then there is no reason for H_{A_i} to move out of its firm. However, $w > w_{\max}$ can attract some H_Y to move into the firm, which would lower the actual demand for, and profit from, durable goods. The symmetric payoff for the firm and its H_{A_i} is thus $\pi_A < \pi_{\min}$.

If firm i pays $w < w_{\max}$, but the true productivity of its H_{A_i} is $w > w_{\max}$, then H_{A_i} moves completely out of the firm. The firm ceases to operate, that is, it loses its patent for the blueprint, and hence its actual profit is zero. H_{A_i} can thus (instantaneously) form another firm and earn positive profits, but at $w > w_{\max}$, this new firm can attract some H_Y into it, thereby decreasing actual profit to π_B. Note, though, that some of the H_{A_i} might transfer to the manufacturing sector, bringing with them the higher productivity $w > w_{\max}$, so that the decrease in H_Y might be partially offset and $\pi_B > \pi_A$. The point is that some H_{A_i} tends to remain in research, so that in this case there is greater potential movement from manufacturing to research than vice-versa. Thus, the decrease in H_Y is not fully offset, implying $\pi_B < \pi_{\min}$.

If firm i pays $w > w_{\max}$ but its H_{A_i} only demands $w_{\max}$, then H_{A_i} need not move out of the firm. Some H_Y could move into the firm, thereby decreasing actual profit to π_C. However, the movement of H_Y can be partially curtailed, since the discrepancy between what the firm originally wanted to pay, $w > w_{\max}$, and what H_{A_i} demands, $w_{\max}$, can be exploited, so that the final wage may not be that much larger than $w_{\max}$. Hence, the movement of H_Y into the firm is limited, or less than the movement when $w_{\max}$ 'meets' $w_{\max}$. Thus, we (still) have $\pi_C < \pi_{\min}$, but $\pi_C > \pi_A$.[38] It is as though a symmetric $w > w_{\max}$ sends

[38] π_C may be greater than, equal to, or less than, π_B, depending on how much the decrease in H_Y is offset in either case.

a clearer signal to H_Y to move into research, while a non-symmetric strategy involving $w > w_{\max}$ creates some hesitation.[39]

3.1.3 Equilibrium Entrants

It can be easily seen that the strategy $w > w_{\max}$ is dominated, and that the two pure Nash equilibrium (N.E.) strategies are the symmetric $w_{\max}$ and $w_{\min}$. If, following Swinkels (1992), we endow the players with some prior rationality, then we can ex-ante disregard $w > w_{\max}$ and re-define the game into a symmetric bi-matrix with (pure) strategies $w_{\max}$ and $w_{\min}$, thereby restricting the competing pure strategies to (Nash) equilibrium 'entrants'.[40] That is, suppose firms face the initial 3×3 game above, they can eliminate the strategy $w > w_{\max}$, since, being a dominated strategy, it cannot be evolutionarily stable in the evolutionary game.[41] Since (the symmetric) $w > w_{\max}$ is not even a Nash equilibrium, it cannot be a best response to a post-entry environment of $(1-\varepsilon)$ adopting $w_{\max}$ and ε adopting $w > w_{\max}$, nor in an environment of $(1-\varepsilon)$ adopting $w_{\min}$ and ε adopting $w > w_{\max}$, where, assuming $w_{\max}$ and $w_{\min}$ are evolutionarily stable strategies (ESS), some small proportion of 'mutants' ε adopting $w > w_{\max}$ cannot successfully invade. This is because in a 'pure' environment, $w > w_{\max}$ already yields strictly lesser profits than $w_{\min}$ and $w_{\max}$, i.e. $\pi_A < \pi_{\min} < \pi_{\max}$. Thus, in any (mixed) post-entry environment where some small proportion of firms enters with $w > w_{\max}$ while the rest adopt $w_{\min}$, or if the rest adopt $w_{\max}$, the expected payoff would be greater than π_A.

Disregarding $w > w_{\max}$ ex ante, we can test the evolutionary stability of the Nash equilibria against each other. The bi-matrix game has three N.E.: the (symmetric) N.E., $w_{\max}$ and $w_{\min}$, and a mixed-strategy $\mu w_{\max} + (1-\mu)\, w_{\min}$. The associated payoff matrix is thus:

$$A = \begin{bmatrix} \pi_{\min} & \pi_{\min} \\ 0 & \pi_{\max} \end{bmatrix}.$$

In section 3.2.1, we identify $w_{\max}$ and $w_{\min}$ by specifying the particular values of γ. The specific bi-matrix games are in a sense 'deterministic', since for every relevant shock and given specific values for r, E, and H_Y, we can pre-calculate two specific values for γ corresponding to $w_{\max}$ and $w_{\min}$, and the associated payoffs $\pi_{\min}$ and $\pi_{\max}$.[42]

[39] Technically, it is enough to assume $\pi_C > \pi_A$, and unnecessary to specify that $\pi_B > \pi_A$, in order for the symmetric strategy $w > w_{\max}$ to be dominated. Intuitively, however, one would expect $\pi_B > \pi_A$ using the same logic justifying $\pi_C > \pi_A$, since a symmetric $w > w_{\max}$ can send a clearer signal to attract H_Y than an asymmetric strategy involving $w > w_{\max}$.

[40] That is, $w_{\max}$ or $w_{\min}$ can 'enter' the environment, i.e. some firms may start adopting these, and may successfully invade by eventually replacing the incumbent wage.

[41] Note that evolutionary stability is a refinement of the Nash equilibrium. Friedman (1991) summarizes the relationship among stable states: $ESS \subset NE \subset FP$, where FP is a fixed point.

[42] Although the value of the strategies are pre-determined, there is still some inherent randomness in the decision process since players do not know each other's simultaneous move but can only rely on expected payoffs when choosing their strategy. Boylan (1992, 1995)

The payoff matrix A describes a coordination game in which there are three nash equilibria (the two pure strategies - $\gamma_{\min}$ which gives $w_{\max}$, and $\gamma_{\max}$ corresponding to $w_{\min}$ - and one mixed strategy). Following Weibull (1995), we can normalize A to form a doubly-symmetric matrix A':

$$A' = \begin{bmatrix} a_1 & 0 \\ 0 & a_2 \end{bmatrix},$$

where $a_1 = a_{11} - a_{22}$ and $a_2 = a_{22} - a_{12}$. Given $\gamma_{\min}$ and $\gamma_{\max}$, the mixed-strategy N.E. is equal to $\gamma_m = \gamma_{\min}\left(\frac{a_2}{a_1+a_2}\right) + \gamma_{\max}\left(1 - \frac{a_2}{a_1+a_2}\right)$.[43]

Among these equilibria, the ESS should satisfy Maynard Smith's (1974) first, (a), and second-order, (b), conditions:[44]

$$u(y,x) \leq u(x,x)\, \forall y \tag{a}$$

$$u(y,x) = u(x,x) \Longrightarrow u(y,y) < u(x,y)\, \forall y \neq x, \tag{b}$$

where assuming x is the (pure or mixed) ESS, and y a (pure or mixed) 'mutant' strategy, then x does better against y than y does against itself. Hofbauer (1979) shows that this is equivalent to having the post-entry payoff of x greater than the post-entry payoff of y:[45]

$$u[x, \varepsilon y + (1-\varepsilon)x] > u[y, \varepsilon y + (1-\varepsilon)x].$$

For ES strategies, there must then exist a minimum value of $\varepsilon > 0$ which can maintain the condition of strict inequality of expected payoffs, and it can be easily seen that only the two pure N.E. strategies are evolutionarily stable. If, say, $\gamma_{\min}$ is the incumbent ESS, for it to remain so when there is possibility of mutation, it must be that the proportion of mutants adopting $\gamma_{\max}$ is small enough, i.e. ε can take on values $0 < \varepsilon < \frac{a_2}{a_1+a_2}$ while keeping the post-entry payoff of $\gamma_{\min}$ strictly greater than that of $\gamma_{\max}$. If we allow the proportion to evolve as v, any value $\frac{a_2}{a_1+a_2} < v < 1$ reverses the inequality, making $\gamma_{\max}$ the new ESS.[46] Thus, both of the pure-strategy Nash equilibria are ESS. However, the post-entry payoff of mixed strategy γ_m is always equal

points out that by the law of large numbers it is as if players behave as expected. In Desierto (2005b) we propose an explicitly stochastic model in which selection of strategies need not follow expected payoffs, although the value of the pure strategies may still be pre-determined. That is, individual players may make mistakes in choosing between the *given* pure strategies.

[43] By normalization, Weibull (1995) shows that general symmetric 2x2 games can be categorized with respect to best-reply properties into any of three games: prisoner's dilemma, coordination game, and the hawk-dove game.

[44] Note that x here denotes a strategy and does not refer to the level of durable good supplied.

[45] The post entry payoffs can be seen as expected payoffs to a player, $u(e^x, \varepsilon)$ and $u(e^y, \varepsilon)$, given the post-entry population state/profile of ε proportion of mutants (and $(1-\varepsilon)$ non-mutants), or the probability that there will be εn mutants (and $(1-\varepsilon)n$ non-mutants). Such interpretation is comparable to that in the Replicator Dynamics (RD) where the population state evolves. Thus, $u[x, \varepsilon y + (1-\varepsilon)x]$ is the expected payoff of playing x, and $u[y, \varepsilon y + (1-\varepsilon)x]$ the payoff of playing y, when the population profile is $\varepsilon y + (1-\varepsilon)x$.

[46] See following section on the Replicator Dynamics on how the proportions evolve.

to that of alternative pure or mixed strategy y for every value of ε, because each y is a best response to γ_m. That is, there is no value of ε that satisfies $u\left[\gamma_m, \varepsilon y+(1-\varepsilon)\gamma_m\right] > u\left[y, \varepsilon y+(1-\varepsilon)\gamma_m\right]$ for $\gamma_{\min} \leq y < \gamma_m$ except $\varepsilon = 0$, or $u\left[\gamma_m, \varepsilon y+(1-\varepsilon)\gamma_m\right] < u\left[y, \varepsilon y+(1-\varepsilon)\gamma_m\right]$ for $\gamma_{\max} \geq y > \gamma_m$ except $\varepsilon = 1$. Thus, there is no suitable minimum ε that can serve as a barrier to invasions against γ_m, which makes the mixed strategy not an ESS.[47] It is shown in the following sections that the ESS, $\gamma_{\min}$and $\gamma_{\max}$, are asymptotically stable in a complementary Replicator Dynamics (RD).[48]

3.2 The Replicator Dynamics

Suppose an anticipated shock creates uncertainty and thus triggers the dynamics. That is, some firms may be able to start charging a new price by adopting the anticipated interest. They can do so if they are able to exploit inherent adjustment costs of human capital, so that the firms can keep producing and supplying their durable good at a level that can (still) be absorbed by the manufacturing sector. Other firms continue to adopt the same 'pre-shock' price, if they believe this reflects the true adjustment cost of human capital. The adjustment costs depend on the particular level of γ_i at which H_{A_i} is able to produce blueprints. That is, some researchers may be able to produce relatively lower, or higher, general knowledge per blueprint, while the range of γ_i can be pre-determined so that the actual productivity per blueprint of all researchers is contained within $[w_{\min}, w_{\max}]$. Thus, during transition there are two types of pure strategies corresponding to two (pure) firm-types, where each strategy for γ has a compatible pricing strategy for durable goods, and vice-versa. Depending on the evolutionary game and according to the corresponding RD, the aggregate decisions of firms may eventually lead to either a relatively more, or less, effective set of institutions.

3.2.1 Firm-level Decisions

Given r_j, H_{Y_j}, E_j, and γ_j, consider the case of a negative shock - when the 'pre-shock' interest cost is less than the anticipated interest cost, i.e., $r_j < r_{ja}$.[49] Note that pure strategies imply compatibility of a firm with its own researchers, so that researchers remain within the firm. Let one pure strategy correspond to the case when H_{A_i} believes the (relatively higher) r_{ja} should be reflected in the value of blueprints. That is, with pre-shock profit $\pi^* = f\left(r_j, H_{Y_j}, E_j, \gamma_j\right)$ (calculated from equation 17), suppose H_{A_i} believes P_{A_j} should fall to $\frac{\pi^*}{r_{ja}}$. Then this implies that at the same pre-shock wage, H_{A_i} can produce blueprints at a

[47] For more on invasion barriers, see Weibull (1995).

[48] By Hofbauer, et.al (1979), all ES states are asymptotically stable in the RD, but not necessarily vice-versa.

[49] To compute for wages and profits we also need the particular values for L_j and parameters α, β, and δ, but we take these as fixed all throughout.

new, relatively lower level (i.e. higher quality) of $\gamma_{ja} < \gamma_j$. In other words, let γ_{ja} be that particular level which keeps the pre-shock wage fixed given the belief of a new $\frac{\pi^*}{r_{ja}}$, which can also be calculated using equation (16) but replacing r_j with r_{ja}. Because γ_{ja} has 'absorbed' the shock r_{ja}, there is no need or opportunity for the firm to pass on the effect of the shock to the manufacturing sector in the form of higher mark-up on the price of the firm's durable goods. That is, γ_{ja} validates π^*, since the potential increase to r_a is entirely offset by the decrease (improvement) of γ_j to γ_{ja}. To obtain the pre-shock profit π^*, the firm thus keeps pricing its durable goods at the pre-shock price using r_j (p_j from equation 6) and supplying them at the original level (x_j from equation 7). Earning the same π^* and pricing at r_j means that the firm does not actually lower P_{A_j} as H_{A_i} had believed, but keeps the pre-shock $P_{A_j} = \frac{\pi^*}{r_j}$. Thus, (using equation 3) the actual productivity per blueprint of H_{A_i} is now equal to $\frac{w_{H_{A_j}}}{A_j} = \frac{\delta\pi^*}{r_j E_j^{\gamma_{ja}}}$, which is greater than the pre-shock level $\frac{w^*_{H_{A_j}}}{A_j} = \frac{\delta\pi^*}{r_j E_j^{\gamma_j}}$, since $\gamma_{ja} < \gamma_j$. Since even at this new, relatively higher, wage, the same level H_{Y_j} can still be kept in manufacturing, we can thus set the maximum wage, $w_{\max}$, equal to this, i.e. $w_{\max} = \frac{\delta\pi^*}{r_j E_j^{\gamma_{ja}}}$. We can also break down H_{A_i}'s productivity per blueprint into $w_{\max} = \frac{\delta\pi^*}{r_{ja} E_j^{\gamma_{ja}}} + \left[\frac{\delta\pi^*}{r_j E_j^{\gamma_{ja}}} - \frac{\delta\pi^*}{r_{ja} E_j^{\gamma_{ja}}}\right]$, where we can define the first term as $w_{\min}$, or the minimum amount that H_{A_i} can earn should it move out of its current firm, while the difference in brackets is the amount that goes to H_{A_i}'s 'efforts' to improve institutional quality. Note that $w_{\min} = \frac{\delta\pi^*}{r_{ja} E_j^{\gamma_{ja}}}$ is also equal to the pre-shock wage $\frac{w^*_{H_{A_j}}}{A_j} = \frac{\delta\pi^*}{r_j E_j^{\gamma_j}}$ since γ_{ja} is the exact amount that keeps $\frac{w^*_{H_{A_j}}}{A_j}$ fixed given r_{ja}.[50]

The other pure strategy, on the other hand, corresponds to the case when H_{A_i} believes that the true price of blueprints should remain at its pre-shock value $P_{A_j} = \frac{\pi^*}{r_j}$. There is thus no need for H_{A_i} to change γ_j in order to keep earning the pre-shock wage. However, in this case, the firm, while keeping pre-shock wage fixed and thus preventing any movement in human capital, can pass on the shock to the manufacturing sector by adopting the new price p_{ja} (computed from equation 6 using r_{ja}) for its durable goods, and supplying at a new level x_{ja} (computed from equation 7 using r_{ja}). The firm can then earn a profit level π_a that is higher than the pre-shock π^*, but by also using r_{ja} to discount its profit, the price of the blueprint remains the same as the pre-shock level, i.e. $P_{A_j} = \frac{\pi_a}{r_{ja}} = \frac{\pi^*}{r_j}$. Its H_{A_i} earns the same wage per blueprint equal to

[50] Since γ is constrained between 0 and 1, we only consider shocks that are not 'too big'. That is, the difference between r_{ja} and domestic r_j should not be too large as to require a new level of γ that is less than 0 or greater than 1. It is possible to show that in case of very large shocks, the new level of γ takes either 0 or 1 and any remaining 'effect' of the shock can then be absorbed by some inter-sector movement of human capital. Such cases, however, are not illustrated here.

$\frac{\delta \pi_a}{r_{ja} E_j^{\gamma_j}}$, which is also equal to $w_{\min} = \frac{\delta \pi^*}{r_j E_j^{\gamma_j}}$, since in this case the increase in profit to π_a has entirely captured the increase of interest cost to r_{ja}. Thus, at the same pre-shock level γ_j, H_{A_i} is paid exactly the minimum wage it can get if it moves out of its firm, and there is no extra compensation since H_{A_i} does not exert extra 'effort' to improve institutional quality.

Note that with both (pure) strategies, the actual price of the blueprints remains at its pre-shock value (although H_{A_i} might believe it should change). It is as if the firm, having paid for the blueprint, commits itself to that price even when a (anticipated) shock occurs.[51] That is, because the shock is anticipated, the firm can maintain the pre-shock price of the blueprint by choosing to either change the price for durable goods, or change its strategy for institutional spending by adjusting γ.[52]

Thus, let pure strategy 1 be γ_{ja}, corresponding to $w_{\max}$ and $\pi_{\min} = \pi^*$, while pure strategy 2 is γ_j, corresponding to $w_{\min}$ and $\pi_{\max} = \pi_a$. Note that $\gamma_{ja} < \gamma_j$. The particular profits for the case when $r_j < r_{ja}$ can thus be captured by payoff matrix $A_{r_j < r_{ja}}$:

$$A_{r_j < r_{ja}} = \begin{bmatrix} \pi^* & \pi^* \\ 0 & \pi_a \end{bmatrix},$$

which describes a coordination game. Playing γ_{ja} (or $w_{\max}$) always yields π^* since H_{A_i} remains in the firm even when H_{A_i} demands a wage that is less than $w_{\max}$. Playing γ_j (or $w_{\min}$), on the other hand, can only yield π_a if the firm (offering $w_{\min}$) is matched with H_{A_i} demanding only $w_{\min}$. Otherwise, H_{A_i} moves completely out of the firm, which effectively cancels the firm's right to produce and supply the durable good, thereby driving actual profit down to zero.

From the foregoing analysis, it is easy to illustrate the case of a positive shock, or when $r_j > r'_{ja}$. Again, let pure strategy 1 correspond to $w_{\max}$ and $\pi_{\min}$, and pure strategy 2 to $w_{\min}$ and $\pi_{\max}$, although the particular maximum and minimum values differ from the first case. The new γ'_{ja} is still calculated as the value that keeps pre-shock wage per blueprint constant, given H_{A_i}'s belief of a now relatively lower price of blueprint equal to $\frac{\pi^*}{r'_{ja}}$. Since $r_j > r'_{ja}$, $\gamma'_{ja} > \gamma_j > \gamma_{ja}$, that is, the new strategy that can challenge incumbent γ_j is associated with a deterioration of institutional quality. This, however, preserves (or validates) the pre-shock profit π^*. The alternative strategy, incumbent γ_j, on the other hand, yields a new lower profit level, $\pi'_a < \pi^*$. Keeping γ_j fixed, the firm absorbs the (positive) shock $r_j > r'_{ja}$ by adopting the relatively lower r'_{ja} for its price and the discount cost of profit and earning π'_a.

[51] Durable-good firms, however, can 'renege' on any price for the durable good which it might have promised to the manufacturing sector since there is uncertainty as to the correct r, and hence, the correct mark-up price. That is, it can change its durable-good price since the particular adjustment costs we have assumed are such that they prevent movement of H_Y into research.

[52] An unanticipated shock, on the other hand, would lead to a re-pricing of blueprints. In this case, there is an 'excuse' for changing the price that has been paid or agreed upon since, after all, the shock could not be anticipated.

With pure strategy γ'_{ja}, the productivity per blueprint of H_{A_i} is lower than the pre-shock level, i.e. $\frac{\delta\pi^*}{r_j E_j^{\gamma'_{ja}}} < \frac{\delta\pi^*}{r'_{ja} E_j^{\gamma'_{ja}}} = \frac{\delta\pi^*}{r_j E_j^{\gamma_j}}$. Recall that under this strategy H_{A_i} changes the incumbent γ_j in the belief that P_{A_j} should change. Since P_{A_j} actually stays the same, and $r_j > r'_{ja}$, then at relatively higher γ'_{ja} but fixed P_{A_j} , the wage of H_{A_i} is relatively lower than the pre-shock level. Thus, in this case, $w_{\min} = \frac{\delta\pi^*}{r_j E_j^{\gamma'_{ja}}}$, while $w_{\max} = \frac{\delta\pi'_a}{r'_{ja} E_j^{\gamma_j}} = \frac{\delta\pi^*}{r_j E_j^{\gamma_j}}$, or the pre-shock level.[53]

Thus, when $r_j > r'_{ja}$, pure strategy 1 is now γ_j, corresponding to $w_{\max} = \frac{\delta\pi'_a}{r'_{ja} E_j^{\gamma_j}}$ and $\pi_{\min} = \pi'_a$, while pure strategy 2 is γ'_{ja}, corresponding to $w_{\min} = \frac{\delta\pi^*}{r_j E_j^{\gamma'_{ja}}}$ and $\pi_{\max} = \pi^*$. The profit levels that can be obtained are summarised by payoff matrix $A_{r_j > r'_{ja}}$:

$$A_{r_j > r'_{ja}} = \begin{bmatrix} \pi'_a & \pi'_a \\ 0 & \pi^* \end{bmatrix}.$$

Both $A_{r_j < r_{ja}}$ and $A_{r_j > r'_{ja}}$ follow the general coordination-game structure of matrix A from section 3.1.3. That is, given the anticipated shock to the interest cost, institutional quality may or may not change. Note, though, that we have assigned strategy 1 as the relatively lower level of $\gamma_{\min}$, while strategy 2 is the relatively higher level $\gamma_{\max}$. This is useful as we can then label type 1 firms as the more 'competitive' firms relative to type 2 firms. That is, type 1 firms, whose human capital produce relatively more general knowledge or at a higher 'quality' per type of durable good, have higher productivity than type 2 firms.[54]

The transitional dynamics describe the continuous play of the coordination game described above. Given the above profile of a large enough number of firm-players, $n_j = 2N_j$, we can approximate the evolution of strategies as Taylor and Jonker's (1978) deterministic RD in which pure strategies 1 and 2 are replicated in the population according to how they perform against the average strategy.[55] Suppose, then, that $v_1 = \frac{n_1}{n}$ is the proportion of firms playing strategy 1 and $v_2 = \frac{n_2}{n}$ the proportion playing 2. The population state $V(t)$ is defined as the vector $V(t) = [v_1(t), v_2(t)]$, which can be seen as a mixed strategy for the population. The expected payoff to pure strategy 1 when the population is in state $V(t)$ is $u(e^1, V)$ and the expected payoff to pure strategy 2 is $u(e^2, V)$. The population average payoff, which may be interpreted as

[53] The difference $w_{\max} - w_{\min}$ is foregone by H_{A_i} if it adopts γ'_{ja}. It is as if an additional $w_{\max} - w_{\min}$ is 'diverted' from H_{A_i} to rent-seeking activities so that the same previous profit level π^* can be preserved at the expense of an overall glut in (inefficient) institutional spending and consequent deterioration of institutional quality. (It is 'additional' since whenever $\gamma > 0$, there is already an implicit amount that goes to the 'environment'. Recall discussion in section 2.)

[54] Applied to the open economy model in Desierto (2005), type 1 firms would be the more globally-competitive firms, i.e. those that would be better able to supply to the global/regional economy inasmuch as their durable goods have higher general, than specific, technology component.

[55] We again follow Weibull's (1995) exposition.

the payoff of a 'representative' firm randomly drawn from the population is $u(V,V) = \sum v_i u(e^i, V), i = 1, 2$.

Note that since we are interested in the growth of firm-types (and not profits per se), we can interpret the profit $\pi_{\min}$ as one type-1 firm, and describe a type-2 firm in terms of one type-1 firm. That is, we can divide the normalised payoff matrix A' by $\pi_{\min}$ in order to treat payoffs as the count of 'offspring' produced, i.e. the number of firm/profit-types that are 'replicated', each time a particular strategy for γ is adopted:[56]

$$A_{RD} = \begin{bmatrix} 1 & 0 \\ 0 & \frac{\pi_{\max}-\pi_{\min}}{\pi_{\min}} \end{bmatrix}.$$

From payoff matrix A_{RD}, the pure payoffs used for the RD are thus $u(e^1, e^1) = 1$ for strategy 1 ($\gamma_{\min}$) and $u(e^2, e^2) = \frac{\pi_{\max}-\pi_{\min}}{\pi_{\min}}$ for strategy 2 ($\gamma_{\max}$). Thus, let n_1 represent the number of players that can expect to 'breed' offspring, or to realise payoff, of $u(e^1, V)$.[57] If the payoffs are the "incremental effects of playing the game in question" (Weibull 1995), then the sub-population of players adopting strategy 1 is increased by replicating payoff $u(e^1, V)$ captured in the population. If 'reproduction' is continuous, then n_1 grows as: $\dot{n}_1 = [u(e^1, V)] n_1$. Similarly, the growth of n_2 is $\dot{n}_2 = [u(e^2, V)] n_2$, while the growth of n follows $\dot{n} = [u(V,V)] n$. To derive the equations for growth of shares v_1 and v_2, we take the time derivative of the identity $n(t) v_i(t) = n_i(t), i = 1, 2$: $n\dot{v}_i = \dot{n}_i - \dot{n} v_i$. Substituting the growth dynamics into the latter and dividing by n, the RD is thus equal to:

$$\dot{v}_i = [u(e^i, V) - u(V,V)] v_i. \tag{18}$$

This relationship tells us that firm-types (or pure strategies) that earn payoffs greater than the average are growing, while firm-types that have payoffs lower than the average are decreasing. Using the normalized payoff matrix A_{RD}, we obtain:[58]

[56] Note that the RD is invariant under positive affine transformations (Weibull 1995), which allows us to use A_{RD} in lieu of matrix A'. A_{RD} is a more appropriate interpretation of payoffs as we are concerned with the replication of strategies, not profits. Strictly, although firms earn profits, human capital obtain payoffs in the form of the 'compatible' wages. Modeling the growth of profits would thus be misleading. Also, A_{RD} is more suitable for our (continuous-time) RD since profit levels can be very large, and using A can produce large (discrete) adjustments per time period. (See Vega-Redondo 1996 for an analysis of the discrete-time and continuous-time RDs.)

[57] The 'firms' and their human capital, being the players of the game, earn the payoffs - the firms in terms of profits, and human capital in terms of the corresponding wages. Thus, $\pi_{\min}$ for the 'firm', for instance, is translated into $w_{\max}$ for its human capital player. (Note that the term "firm-types" refer to all players, and are thus applied to both the 'firms' and their human capital.)

[58] From the normalized payoff matrix A_{RD}, expected payoffs are thus $u(e^1, V) = v_1 + 0v_2$ and $u(e^2, V) = 0v_1 + \left(\frac{\pi_{\max}-\pi_{\min}}{\pi_{\min}}\right) v_2$. Population average payoff is thus $u(V,V) = v_1 v_1 + v_2 \left(\frac{\pi_{\max}-\pi_{\min}}{\pi_{\min}}\right) v_2$, and $\dot{v}_1 = u(e^1, V) - u(V,V) v_1 = v_2 v_1 \left[v_1 - \left(\frac{\pi_{\max}-\pi_{\min}}{\pi_{\min}}\right) v_2\right]$, and $\dot{v}_2 = u(e^2, V) - u(V,V) v_1 = v_2 v_1 \left[\left(\frac{\pi_{\max}-\pi_{\min}}{\pi_{\min}}\right) v_2 - v_1\right]$, since the sum of the population shares necessarily equals one: $(1 - v_1) = v_2$.

$$\dot{v}_1 = \left[v_1 - \left(\frac{\pi_{\max} - \pi_{\min}}{\pi_{\min}} \right) v_2 \right] v_1 v_2, \tag{18a}$$

$$\dot{v}_2 = \left[\left(\frac{\pi_{\max} - \pi_{\min}}{\pi_{\min}} \right) v_2 - v_1 \right] v_1 v_2. \tag{18b}$$

It can be seen from equation (18a) that $\dot{v}_1$ changes signs when $v_1 = \left(\frac{\pi_{\max} - \pi_{\min}}{\pi_{\min}} \right) v_2$, i.e., at the mixed-strategy N.E. $v_1 = \frac{\pi_{\max} - \pi_{\min}}{\pi_{\max}}$. This means that for an initial proportion of firms adopting $\gamma_{\min}$ that is equal to $v_1^0 < \frac{\pi_{\max} - \pi_{\min}}{\pi_{\max}}$, v_1 decreases to zero (while v_2 increases to one), but for a large enough initial proportion $v_1^0 > \frac{\pi_{\max} - \pi_{\min}}{\pi_{\max}}$, the population share v_1 grows towards one (while v_2 declines to zero). Depending on the initial proportions adopting either strategy, the asymptotically stable strategy is either $\gamma_{\min}$ or $\gamma_{\max}$.Thus, the population state converges to either of the two possible ES strategies discussed in the previous section. Indeed, if, for example, $\gamma_{\min}$ becomes the evolutionarily stable strategy, then by Hofbauer, et. al. (1979), it should have also satisfied the RD. It can be seen that if $\gamma_{\min}$ satisfies $u\left[\gamma_{\min}, \varepsilon\gamma_{\max} + (1-\varepsilon)\gamma_{\min}\right] > u\left[\gamma_{\max}, \varepsilon\gamma_{\max} + (1-\varepsilon)\gamma_{\min}\right]$, that is, if there is a minimum proportion of non-mutants,$(1-\varepsilon)$, or a maximum proportion of mutants, ε, with which the latter inequality holds, then $\gamma_{\min}$ necessarily satisfies $u\left(e^{\gamma_{\min}}, V\right) > u\left(e^{\gamma_{\max}}, V\right)$, since $v_1 = (1 - v_2) \geq (1 - \varepsilon)$.[59]

Equation (18) also provides the firms' speed of 'learning' the 'correct' strategy, which is decreasing as the expected payoff to adopting the correct strategy approaches the population average payoff. That is, the rate of adjustment is higher near the onset of the shock, and tapers off as the new steady state is reached. In addition, it can be shown that the larger the absolute value $\left| v_1^0 - \frac{\pi_{\max} - \pi_{\min}}{\pi_{\max}} \right|$, the faster the system approaches the steady state.[60]

3.2.2 Aggregate Growth

[59] $u\left(e^{\gamma_{\min}}, V\right) > u\left(e^{\gamma_{\max}}, V\right)$ implies asymptotic stability of $\gamma_{\min}$ in the RD, since in this case, $u\left(e^{\gamma_{\min}}, V\right)$ is necessarily greater than, and $u\left(e^{\gamma_{\max}}, V\right)$ less than, the average of the two expected payoffs.

[60] See ch. 2 of Desierto (2005) for simulations, where different initial values of proportions have been assumed. While we have not explicitly done so, it may be interesting to test for possible determinants of v_1^0. Note, also, that the RDs (18a) and (18b) may be seen as continuous-time approximations of discrete adjustments. First of all, each 'draw' or pair-wise matching reflects adjustment periods, or how often strategies on wages, price and profits are reviewed, i.e. annually, monthly, weekly etc. Secondly, recall that playing the game may entail 're-organisation' of the firm and/or the intra-sector movement of researchers when strategies do not match. In reality this can be subject to inherent rigidities, making each 'draw' or pair-wise matching to be few and far between so as to render the game more discrete than continuous. Vega-Redondo (1996) provides a discrete-time version of the RD: $v_i(t+1) - v_i(t) = \frac{\left[u\left(e^i, V\right) - u(V,V)\right] v_i}{u(V,V)}$, which may be more appropriate, if we let t denote adjustment periods. Thus, depending on review rates and intra-sector mobility, it can take a very long time for the system to stabilise.

In computing the growth rate of output Y_j during the transition, note that both knowledge A_j and level x_j at which durable goods are supplied are now evolving at rates that are influenced by the RD. This is because there is a proportion of firms, v_1, that produce new knowledge with a greater general, relative to specific, component, i.e. at $\gamma_{\min}$, and a proportion, v_2, that produce at the mix $\gamma_{\max}$. While in the steady state, all firms share all knowledge, the transition reveals heterogeneity in human capital productivity which dichotomises the research/durable good sector. The total stock of knowledge produced by all firms is now $A_j = v_1 A_1 + v_2 A_2$, where A_1 refers to knowledge that is produced by type-1 firms using the mix $\gamma_{\min}$, while A_2 is knowledge produced by type-2 firms using $\gamma_{\max}$. Thus, while all researchers still share the same environment, the types of technology produced now differ between sub-sectors. Although at first glance it seems that the spillover effects of technology are curtailed in that $A_1 \neq A_2$, note that there is a positive externality generated as v_1 increases. That is, firms that initiate efforts to improve (or keep a relatively higher) institutional quality bear the greatest uncertainty of earning relatively lower profits while, assuming there is sufficient 'momentum', i.e. $v_1 > mixed\ N.E.$, the remaining uncertainty decreases for the other firms as expected payoff approaches pure payoff of strategy 1, making it 'easier' for other firms to follow. In other words, it is as if firms 'free-ride' on the initiators' efforts.[61] Thus, while the quantity of technology may initially decrease with dichotimisation, its quality can improve (along with the quantity of the higher-quality type A_1), thereby increasing aggregate A_j.

Durable goods are now also supplied at two levels. The proportion v_1 that uses the relatively lower mark-up for the price of its durable goods supply at a higher level, x_1, while the v_2 proportion of firms use the relatively higher mark-up and supply at the lower level, x_2. Since there is only one manufacturing sector, the aggregate level of durable good that is 'absorbed' by the manufacturing sector is the average $x_j = v_1 x_1 + v_2 x_2$.[62] Output during the pre-integration transition is thus:

$$Y_j = H_{Y_j}^{\alpha} L_j^{\beta} \left[v_{1t} A_1 + v_{2t} A_2 \right] \left[v_{1t} x_1 + v_{2t} x_2 \right]^{1-\alpha-\beta}. \tag{19}$$

Recall that in the steady state $\frac{\dot{Y}_j}{Y_j} = \frac{\dot{A}_j}{A_j}$ which is also equal to the growth rate of capital K_j. During transition, however:

$$\frac{\dot{Y}_j}{Y_j} = \frac{\dot{A}_j}{A_j} + \frac{(1-\alpha-\beta)\,\dot{x}_j}{x_j}, \tag{20}$$

while $K_j = \eta A_j x_j$ grows at the rate:

[61] Recall that the RD is fastest at the beginning, and tapers off as it reaches the steady state.

[62] However, as seen in Desierto (2005), if markets open up to the global economy, there may eventually be two distinct manufacturing sectors, a domestic sector that uses only domestic durable goods (and produces only domestic goods), and a global sector using global durable goods (and manufactures for the global market). Similarly, there may be a domestic, and a global, research/durable good sector.

$$\frac{\dot{K}_j}{K_j} = \frac{\dot{A}_j}{A_j} + \frac{\dot{x}_j}{x_j}, \tag{21}$$

where

$$\dot{A}_j = \frac{\delta v_1 H_{A_j} A_1}{E_j^{\gamma_{\min}}} + \dot{v}_1 A_1 + \frac{\delta v_2 H_{A_j} A_2}{E_j^{\gamma_{\max}}} + \dot{v}_2 A_2, \tag{22}$$

$$\dot{x}_j = \left[\frac{(1-\alpha-\beta)^2 H_{Y_j}^{\alpha} L_j^{\beta}}{\min(r_j, r_G)} \right]^{\frac{1}{\alpha+\beta}} \dot{v}_1 + \left[\frac{(1-\alpha-\beta)^2 H_{Y_j}^{\alpha} L_j^{\beta}}{\max(r_j, r_G)} \right]^{\frac{1}{\alpha+\beta}} \dot{v}_2, \tag{23}$$

and the RDs are given by equations (18a) and (18b).

It is seen here that capital grows at a different rate than output; that is, capital accumulation is either slower, or more rapid, during transition, until it eventually increases or slows down to reach its steady state growth. (Note that in the steady state when either $\dot{v}_1$ or $\dot{v}_2$ equals zero, $\dot{x} = 0$, and only continuous technological change can sustain further growth.) The intuition behind this lies in the feature that whenever institutional quality evolves, not only does the quantity of the types of durable goods (A) increases, but the 'quality' of each type evolves as well, allowing the level x at which durable goods are supplied to change. For instance, a higher quality-type A_1 'allows' the firm to supply the durable good at a higher level (using a relatively lower interest cost and mark-up price). During adjustments toward the steady state, we make explicit an additional function of human capital - that of determining the relative mix of general and country-specific knowledge in every blueprint and durable good produced. That is, human capital does not only produce more durable goods, they do so with relatively higher or lower general knowledge component, which enables firms to supply durable goods at different qualities. Because of this 'extra' function of human capital during transition, there is 'unbalanced' growth. As the 'correct' strategy for γ is learnt by all firms, this becomes a 'convention' (an ESS) and eventually becomes fixed in the steady state, and the productivity of human capital will then only pertain to the continuous production of blueprints, at a constant mix of (fixed) γ.

It can also be seen that a path leading to $\gamma_{\min}$ (when $v_1 = 1$ and $n_1 = 2N$, and $v_2 = 0$ and $n_2 = 0$) leads to a relatively higher growth of A_j, and a relatively higher level of x_j, in the steady state. Note, however, that such a path is associated with a relatively lower level of profits, i.e. $\pi_{\min}$. Higher output growth can thus be achieved even at the expense of durable-good firm profits. This should be intuitively clear, as firms that improve institutional quality absorb more of the negative shock (or forego benefits from a positive shock) than firms who do not. That is, as noted earlier, it is as if firms that take longer to adjust to $\gamma_{\min}$ 'free-ride' on the initiating firms' efforts, or to put it another way, initiating firms produce (positive) externalities for the aggregate economy. The larger the total initial effort (to improve institutional quality) or initial 'sacrifice' of profits, the greater the external benefits generated, and the larger and faster the increase in aggregate output.[63]

4 Interpretation

The evolution into more, or less, effective institutions can thus be shown as a continuous (evolutionary) game between firms (existing and potential, i.e. the firms that researchers can form if they move out of their current firm), which eventually determines the type of firm and corresponding strategy that can survive. The game is essentially one of coordination, with better institutions associated with lower level of profits (implying lower interest/transaction cost) but higher wage of researchers, and less effective institutions with higher profits (implying higher interest/transaction cost) but with lower wage. Anticipated changes in the interest cost trigger the game by allowing firms to either maintain the previous level of institutional quality and let the interest cost (and mark-up price and profits) change, or change institutional quality to prevent the change in the interest cost. The latter 'adaptive' response requires an improvement in institutional quality when the anticipated shock is negative, but 'allows' a worsening of institutional quality when the shock is positive.

Both strategies are evolutionarily stable. That is, firms that initiate an upgrade into (or keep) better institutions can succeed in pulling the rest of the firms into adopting the same strategy and similarly, efforts that lead to a deterioration (or non-improvement) of institutions can spread into the aggregate. The potential direction and magnitude of the change is determined by the type of the shock, while the success of the corresponding strategies depends on the initial efforts of (initiating) firms. If the proportion of initiating firms is large enough, then the expected profits of adopting their strategy is larger than the expected profits from not following, which then eventually 'convinces' all firms (and their researchers) of the correctness of the strategy.[64] When firms anticipate an increase in the interest cost ($r_j < r_a$), they can initiate efforts to improve institutions to stay relatively competitive by essentially raising the productivity of their researchers. It is as if the extra compensation to researchers goes to efforts to keep interest/transactions costs at the relatively lower level r_j.[65] This

[63] This is demonstrated in the simulation results in Desierto (2005).

[64] This 'expected' payoff interpretation, in which as if a firm surveys the 'field' to compute for the population average payoff and compares this to the pure strategies' expected payoffs, yields the same results as in our pair-wise interpretation where each firm pits its strategy against that of its 'pair'. (It is then as if the firm tests the pure strategy against the mixed strategy corresponding to the population state.) In the aggregate, the dynamics (still) prescribes that the replicator (or pure strategy) that yields a payoff greater than the average grows. (See Weibull 1995.) For an alternative 'playing-the-field' setup of a pair-wise game, see Vega-Redondo (1996).

[65] That is, human capital may be compensated for additional efforts spent on, for example, initiating changes in financial institutions (e.g. the venture capital innovation), or on lobbying for certain laws (e.g. anti-piracy laws and stricter enforcement of intellectual property rights), which can ultimately lower transaction costs for all technology firms. Firms can also spend on relocating into concentrated clusters of research/durable-good firms (to keep the 'factor'

would allow the firms to price their durable goods at a relatively lower, more competitive, price.

On the other hand, if firms anticipate a decrease in the interest cost ($r_j > r_a$), then some firms may actually initiate efforts that lead to a deterioration in institutions by 'diverting' some of the intended compensation of human capital in order to keep the (relatively higher) interest cost r_j and price, thereby keeping the relatively higher profits. That is, 'bad' institutions incur higher transactions costs for the firm, which the latter can then pass on to its buyers (the manufacturing sector), and this can give firms the incentive to keep institutions relatively ineffective.[66] It is as if these firms become 'complacent' that they will still be able to supply in the economy since they believe/anticipate that interest costs will decrease. (However, if all other firms do the same, then the interest cost will not decrease to r_a but instead remain at r_j.)

Note that the possibility of evolution of institutional quality relies on the assumption of asymmetric mobility of human capital.[67] That is, if inter-sector movement is more costly than the cost of moving from one research firm to another, then human capital, while kept within the research/durable good sector, has the opportunity to change the quality of the blueprints they produce in anticipation of a shock. To put it in another way, the anticipated shock can induce some uncertainty as to the true productivity of researchers, which can thus present an opportunity for firms to 'learn' their productivity in the aggregate.

Thus, there are two types of learning involved in the transition dynamics. That is, while the quantity of blueprints increase, their quality also changes as institutional quality evolves.[68] This (transitional) co-evolution of knowledge and institutions is what drives the growth of aggregate output during this out-of-steady state version of the Romer (1990) model. In this alternative framework, firms not only increase the number of (domestic) blueprints, but they also learn the correct mix (of general and specific components) at which each blueprint should be produced, which reflects the true 'stable' quality of institutions. The more effective institutions become, the more 'general' the blueprints and the more readily it is absorbed without having to produce more country-specific knowledge in order to adapt to the environment. Thus, in this case, technology-creation is faster and output growth is higher.

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intensity of the shared environment low), as exemplified by Silicon Valley.

[66] Such firms may then pursue excessive rent-seeking by, for example, lobbying for protectionist laws, or engaging in 'corrupt' and bureaucratic practices that can undermine rights and patents over blueprints, in order to justify the higher transactions cost which they effectively face. That is, instead of raising human capital productivity, such firms may want to 'protect' profits.

[67] The presence of large wage inequalities in transition and developing economies, and during increased economic integration, may be telling. However, note that the relevant wages would be those of skilled labour, i.e. those engaged in innovation and those alternatively employed in high-level managerial positions. In this respect, large wage inequalities between skilled and un-skilled workers do not necessarily indicate drastic changes in institutional quality, although they can hasten the evolution (into relatively better, or worse, institutions).

[68] Note that the higher the quality of institutions, the higher the quality of the blueprints.

5 Conclusions

In this paper we have extended the Romer (1990) model to account for (endogenous) institutional change and explained transitional dynamics towards the steady state by modeling the co-evolution of institutions and technology. We have also been able to show knowledge-creation as both increases in the types of goods and improvements in quality. That is, during transitions, (monopoly) profits can be continuously eroded, as institutions become more effective, so that the (aggregate) quality of blueprints can continuously increase. At the steady state, when there is a fixed level of institutional quality, all firms face the same fixed interest cost and earn the same profit level. Hence, output growth can now only rely on the increase in the number of types of (durable) goods that are available at the same 'quality'.

Note that the change in institutional quality is triggered by an anticipated change in the interest cost. If the interest cost were to change unexpectedly, then no firm would be able to anticipate. It is as if all players would simultaneously make the mistake of not changing the level of γ. All the firms' wages would equally decrease or increase, thus prompting inter-sector movements of human capital (between manufacturing and research) until the new equilibrium is reached. Other unanticipated shocks, such as changes in the level of total human capital, and the environment, could also affect equilibrium productivity and wages. Such dynamics, however, have not been analysed in this paper.

Although we have only considered singular shocks, the transition dynamics proposed here could be easily applicable to multiple shocks. If the shocks occurred simultaneously, the dimensions of the bi-matrix game could be extended, such that there could be more than one anticipated interest cost, or to preserve the bi-matrix framework, an 'average' anticipated interest cost could be calculated which could capture the 'average' anticipated effect of the shock. On the other hand, if shocks occurred one at a time, they could be treated as different games. However, note that once the economy starts the proposed Replicator Dynamics, it remains in transition, since the steady state is reached only asymptotically. Thus, the current evolutionary game could still be playing out when and if another shock occurred. One way to resolve this is to terminate the current, and start a new, RD if it could be assumed that the particular source of uncertainty disappears once a new shock hits the economy (and a new source of uncertainty is identified). In another paper (Desierto (2005)) we provide an example of this, where economic integration is modeled as a two-stage Replicator Dynamics, the first-stage being triggered by the anticipation of opening up of markets and is terminated once the economy is actually opened. A second-stage (multi-population) RD follows, in which the new source of uncertainty is the actual global interest cost that will prevail with the participation of the entrant economy in the new integrated region.

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