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R&D and Absorptive Capacity: from Theory to Data*

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Abstract

This paper presents a unified model that integrates the theoretical literature on Schumpeterian endogenous growth, the microeconometric literature on R&D and productivity, and the empirical literature on productivity convergence. Starting from a structural model of endogenous growth following Aghion and Howitt (1992, 1998), we provide microeconomic foundations for a reduced-form equation for Total Factor Productivity (TFP) growth that is commonly used in the empirical literature. We allow a role for R&D in innovation and technology transfer (absorptive capacity). The analysis suggests that many existing studies underestimate R&D's social rate of return and provides an explanation for long-run productivity levels at the industry-level.

JEL CLASSIFICATION: O10, O30, O47

KEYWORDS: Absorptive Capacity, Endogenous Growth, R&D, Total Factor Productivity (TFP)

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1. Introduction

This paper presents a single unified model that integrates the theoretical literature on Schumpeterian endogenous growth, the microeconometric literature on R&D and productivity, and the empirical literature on productivity convergence. Starting from a structural model of endogenous innovation and growth following Aghion and Howitt (1992, 1998), we derive a reduced-form econometric equation for rates of Total Factor Productivity (TFP) growth that is similar in form to models that have been estimated empirically at the industry-level.[1] The equation includes terms in the level of R&D, an economy's distance from the technological frontier, and an interaction term between R&D and distance from the technological frontier. While the microeconometric literature on R&D and productivity focuses on the first term (the R&D level), the productivity convergence literature emphasizes the second (distance from the frontier). The structural model implies that both sets of considerations are important and that there exists a third omitted variable - the interaction term. This reflects R&D's role in the absorption or imitation of others' discoveries, a role which has been termed the 'second face of R&D.' The model has clear theoretical predictions which are empirically falsifiable. A role for R&D in promoting absorptive capacity implies a positive and statistically significant coefficient on the interaction term. The values of the estimated coefficients in the reduced-form equation for TFP growth can be directly related to structural parameters of the model. Our analysis suggests that Schumpeterian models of endogenous growth are not only consistent with cross-country evidence on income convergence (as argued by Aghion and Howitt (1998) and Howitt (2000)), but can also explain industry-level results in the empirical literatures on R&D and productivity convergence. Many existing empirical studies underestimate the social rate of return to R&D, in so far as they neglect the second face of R&D. The model may be used to analyze both the determinants of long-run productivity growth and steady-state equilibrium levels of relative TFP at the industry-level.

The theoretical literature on Schumpeterian models of endogenous growth emphasizes the non-rivalrous and partially excludable nature of knowledge.[2] New ideas can be used at zero marginal cost

[1] See, in particular, Cameron (1996), Cameron, Proudman, and Redding (1998), and Griffith, Redding, and Van Reenen (2000).

[2] Key contributions to this literature include Aghion and Howitt (1992), (1996), (1998), Grossman and Helpman (1991a), Jones (1995), Romer (1990), Segerstrom (1998), and Young (1993), (1998). Quah (2000) uses the term infinite expansibility to capture the non-rivalrous nature of knowledge.

in the research sector, while each innovator can appropriate the returns from her discovery through patent protection. At first, such models were believed to be inconsistent with empirical findings of income convergence. However, recent theoretical advances have shown that the Schumpeterian framework can explain income convergence, while also accounting for other stylized facts such as cross-country differences in aggregate productivity. In Aghion and Howitt (1998) and Howitt (2000), convergence is introduced by allowing the size of a quality-augmenting innovation to depend on a firm's distance behind the technological frontier. In this paper, we show how this idea may be developed to capture a role for R&D in promoting absorptive capacity and to enable a structural model of endogenous innovation and growth to be directly related to the empirical literatures on R&D and productivity convergence.

The dependence of the size of quality-augmenting innovations on distance behind the technological frontier relates to the microeconomic literature on the role of R&D in facilitating the absorption or imitation of others' discoveries.[3] Some knowledge is 'tacit', difficult to codify in manuals and textbooks, and hard to acquire without direct investigation. By actively engaging in R&D in a particular intellectual or technological field, one acquires such tacit knowledge ('absorptive capacity') and can more easily understand and assimilate the discoveries of others. Even then, the transfer of technology may be far from automatic. Arrow (1969) cites the example of the jet engine: when plans were supplied by the British to the Americans during the Second World War, it took ten months for them to be redrawn to conform to American usage.[4] This has led authors such as Cohen and Levinthal (1989) to speak of the two faces of R&D: innovation and learning.

Despite substantial informal and historical evidence of the importance of R&D-based absorptive capacity, the idea has received little attention in the microeconometric literature on R&D and productivity at the firm and industry-level. The conventional approach in this literature regresses TFP growth on a measure of R&D activity, where a positive and statistically significant coefficient is consistent with R&D-based innovation generating TFP growth.[5] There is a substantial body of empirical

[3] See, for example, Barro and Sala-i-Martin (1995), (1997), Cohen and Levinthal (1989), Grossman and Helpman (1991b), Neary and Leahy (1999), Parente and Prescott (1994), and Segerstrom (1991).

[4] For further discussion of the role and importance of tacit knowledge in the historical development of technology, see David (1992) and Rosenberg (1982).

[5] Seminal references in this literature include Griliches (1980) and Griliches and Lichtenberg (1984a). Mohnen (1996) provides a recent survey. See Lichtenberg (1993) for an analysis of R&D and growth at the country-level.

work that has sought to estimate the size of inter-industry R&D knowledge spillovers,[6] international or inter-regional R&D knowledge spillovers,[7] and intertemporal R&D knowledge spillovers.[8] However, in each case, the analysis is concerned with the effect of *other agents' R&D* on own productivity, and there has been very little investigation of how *own R&D* affects the absorption of others' discoveries. Exceptions are Cameron (1996), Cameron, Proudman, and Redding (1998), and Griffith, Redding, and Van Reenen (2000), each of which estimates a reduced-form regression equation for TFP growth including both an R&D level term (as in the conventional approach) and an interaction term between R&D and distance from the technological frontier.[9] Griffith, Redding, and Van Reenen (2000), for example, find a positive and statistically significant estimated coefficient on the R&D interaction term. This finding provides evidence of R&D-based absorptive capacity, and is robust across a wide range of different econometric specifications, for a number of different measures of TFP, and after including a series of alternative control variables.

Independent support for these results is provided in firm-level work by Jaffe (1986). In both equations for patents and for firm profits, Jaffe finds a positive estimated coefficient on an interaction term between own R&D and a measure of the potential technology spillover pool (defined as the weighted sum of other firms' R&D, where the weights exploit patent information on the distance of firms in technology space). One implication of the reduced-form regressions for TFP growth is that the social rate of return to R&D will, *ceteris paribus*, tend to be higher in non-frontier countries, where there is the potential for R&D to stimulate TFP growth through technology transfer.[10] This conclusion also receives independent support from Eaton *et al.* (1998), who calibrate a computable general equilibrium model of endogenous innovation and growth to economy-wide data from 21 OECD countries. With the exception of Portugal, social rates of return to R&D are higher in the non-frontier countries.[11] This paper provides microeconomic foundations for the reduced-form TFP

[6] See, for example, Griliches and Lichtenberg (1984b) and the survey in Griliches (1992).

[7] See Coe and Helpman (1995), Eaton and Kortum (1999), Keller (1997), and Jaffe, Trajtenberg, and Henderson (1993).

[8] See, in particular, Caballero and Jaffe (1993).

[9] Cameron (1996) is concerned with the USA and Japan; Cameron, Proudman, and Redding (1998) analyze the UK and USA; Griffith, Redding, and Van Reenen (2000) consider a panel of 14 industries in 12 OECD countries since 1974.

[10] Note that in the microeconometric literature on R&D and productivity, 'social' refers to the *total* rate of return to R&D (the private rate of return plus any externalities).

[11] This raises the question: why do non-frontier countries not undertake more R&D? This issue will be discussed further below. First, there is a potential divergence between private and social rates of return. Second, distance from

growth regression discussed above; we show how this equation may be derived from a structural model of endogenous innovation and growth.

In recent years, the empirical growth literature has seen renewed interest in the existence of cross-country differences in aggregate productivity.[12] Productivity differences are typically found to be large in magnitude and persistent over time. However, controlling for the determinants of steady-state productivity levels, there is substantial evidence of aggregate productivity convergence.[13] A number of country-level studies also emphasize the role of economic variables in promoting absorptive capacity and facilitating productivity convergence. For example, Benhabib and Spiegel (1994) analyze human capital, while Abramovitz (1986) and Temple and Johnson (1998) stress the role of 'social capability'.

In addition to the cross-country literature, there is a substantial body of empirical work on the measurement and convergence of productivity at the industry-level.[14] Evidence is again found of substantial differences in levels of productivity, and the magnitude of these differences typically varies across industries for any individual country. Bernard and Jones (1996a, b) argue that a substantial proportion of the convergence in aggregate TFP is driven by convergence in the services sector. However, Griffith, Redding, and Van Reenen (2000) find that the lack of convergence in manufacturing is sensitive to the assumption of a Cobb-Douglas production technology. Using superlative index number measures of TFP, they find evidence of convergence in seven out of ten manufacturing industries across 12 OECD countries during 1970-94. Other empirical studies that have found convergence at the industry-level include Dollar and Wolff (1994), Dowrick (1989), and Jorgenson and Kuroda (1990). The theoretical and empirical framework of this paper reconciles productivity convergence at the industry-level with endogenous investments in R&D, and shows how a reduced-form convergence regression (augmented with terms in R&D) can be derived from a general equilibrium structural model of endogenous growth. The analysis explains the existence of steady-state differences in relative TFP across countries in individual industries and convergence in TFP levels conditional on the

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the technological frontier is only one potential determinant of incentives to engage in R&D. There are many others, including, in particular, government policy and national institutions.

[12]See, in particular, Acemoglu and Zillibotti (2000), Hall and Jones (1999), and Prescott (1998).

[13]See, for example, Dowrick and Nyugen (1989), Benhabib and Spiegel (1994), and Bernard and Jones (1996a), (1996b).

[14]Examples include van Ark and Pilat (1993), Bernard and Jones (1996a), (1996b), Dollar and Wolff (1994), Dowrick (1989), Hansson and Henrekson (1994), Jorgenson and Kuroda (1990), and Harrigan (1997), (1999).

determinants of steady-state.

The paper is structured as follows. Section 2 presents a simplified overlapping generations version of Aghion and Howitt (1992) with a single intermediate goods sector. Section 3 extends the analysis to incorporate technology transfer from frontier to non-frontier countries and a role for R&D in promoting absorptive capacity. The tractability of the model enables a reduced-form equation for TFP growth of exactly the same form estimated in the empirical literature to be derived. Section 4 extends the analysis to allow multiple final goods sectors. Section 5 discusses the empirical results of a number of studies which have estimated the reduced form regression, and finds that these are consistent with the predictions of the theory. Section 6 concludes.

2. R&D and Innovation

2.1. Introduction

This section presents a simple overlapping generations version of Aghion and Howitt's (1992) model of endogenous growth through rising productivity or product quality. The world consists of a number of countries, indexed by $i \in \{1, ..., N\}$. Each country is populated by a sequence of overlapping generations, indexed by $t \in [1, \infty]$. A generation consists of a large number of consumer-workers (H_i) who live for two periods. Individual workers are endowed with one unit of labour per period and an exogenous quantity of a sector-specific factor of production which we interpret as capital or land (K_i/H_i). Time is indexed by τ, and we choose units for time such that each period of a generation's life lasts for one unit of time.[15]

The economy consists of three sectors: research, intermediate input production, and final goods production. Labour is employed in research and intermediate input production, while final goods output is produced with capital and intermediate inputs.[16] We begin by considering the case of one final good, manufactured from the output of a single intermediate goods sector. A later section extends the analysis to allow many final goods, each of which is produced from the output of its own intermediate sector. Technological change is modelled as a sequence of endogenous improvements in

[15]Generation t is born at some time τ and dies at time $\tau + 2$. In order to simplify notation, we suppress the implicit dependence on time, except where important.

[16]It is straightforward to extend the analysis to allow labour to also be employed in final goods production. This merely complicates the analysis without adding any insight.

the quality or productivity of intermediate inputs.

The timing of agents' decisions is summarized in Figure 1 and is as follows. At the beginning of period 1, workers inherit a stock of knowledge from the previous generation, and decide whether to enter research or intermediate input production. Research and intermediate input production are modelled as specialized activities, and this decision is assumed to be irreversible. Those who enter the intermediate sector, spend period 1 acquiring the general human capital needed to produce intermediate inputs.[17] Those who enter research spend period 1 engaged in uncertain R&D, and all research uncertainty is resolved at the end of period 1. Production and consumption take place in period 2 of workers' lives. If research is successful at the end of period 1, the innovator receives a one-period patent for the new technology. Bargaining takes place with intermediate input producers at the beginning of period 2 about how to divide the surplus from intermediate input production. If research is unsuccessful at the end of period 1, intermediate inputs are produced with an existing technology in period 2. Since knowledge spills over across generations, all individuals in generation t have access to existing technologies. In the case of unsuccessful research, production of intermediate inputs thus occurs under conditions of perfect competition.[18]

<Figure 1 about here>

2.2. Consumer Behaviour

Workers are endowed with one unit of labour per period. The decision whether to enter research or intermediate input production corresponds to a decision about lifetime labour supply. We denote the number of workers entering research by H_{it}^{R} and the corresponding number entering intermediate input production by $H_{it}^{P} = H - H_{it}^{R}$. There is no disutility from supplying labour, and preferences are defined over consumption of the final good. Workers are assumed to be risk neutral, and the lifetime utility of a representative consumer-worker in generation t is thus a linear function of second-period consumption of the final good,

[17] Redding (1999) considers the case where human capital is specific to vintages of technology, and shows that technological change becomes path dependent.

[18] It is also possible to consider patents of more than one period in length (which requires patent rights to be enforced across generations). In this case, bargaining with secondary developers takes place both when fundamental research is successful and when it is unsuccessful. This substantially complicates the analysis, without adding any insight.

$$U_{it} = c_{i2t} \tag{2.1}$$

2.3. Production

Following Aghion and Howitt (1992, 1998), final goods output (y) is produced from intermediate inputs (x) and sector-specific capital (k). Production occurs under conditions of perfect competition and with a Cobb-Douglas technology,

$$y_{i2t} = A_{i2t}.x_{i2t}^{\alpha} k_{i2t}^{1-\alpha}, \qquad 0 < \alpha < 1 \tag{2.2}$$

where A_{i2t} denotes the period 2 productivity or quality of intermediate inputs. Final goods output is assumed to be tradable at zero transport cost, while intermediate inputs and primary factors of production are non-tradeable. We choose the final good for numeraire so that $p_{i2t} = 1$ for all t and for all countries i.

Intermediate goods technologies may vary across countries, although we allow for the possibility of technology transfer below. Technologies in country i are indexed by $m(i) = 0, 1, ...$, which denotes the interval starting with the $m(i)^{\text{th}}$ innovation and ending with the $m(i) + 1^{\text{st}}$. Each innovation is assumed to raise the quality or productivity of the existing technology by a constant proportion $\gamma > 1$. The state of technology in country i in generation t may be indexed by $m(i)$ alone and is simply $A_{i2t} = A_{2m(i)} = \gamma^{m(i)}.A_i(0)$, where we normalize $A_i(0)$ to 1.[19] Intermediate inputs themselves are produced with labour according to a constant returns to scale technology,

$$x_{i2t} = h_{i2t}, \tag{2.3}$$

where h_{i2t} denotes the number of individuals employed in intermediate production in period 2.

2.4. Research

The specification of the research sector is a discrete time analogue of Aghion and Howitt (1992). If H_{it}^R individuals from generation t in country i enter research, we assume that one individual innovates with probability $\lambda_i H_{it}^R$ and receives the patent to the new technology. Conditional on

[19] To simplify notation, we will suppress the implicit dependence of m on i, except where important.

entering the research sector, the probability that any one individual obtains the patent is thus λ_i (where $0 < \lambda_i < 1$ for all i).[20] Research is an inherently uncertain process, and the parameter λ_i captures the productivity of research, which may vary across countries as a result, for example, of differences in institutions and government policy.

2.5. General Equilibrium

2.5.1. Definition of Equilibrium

General equilibrium is a set of prices for final goods output, intermediate inputs of quality $k \leq m$, workers producing intermediate inputs of quality $k \leq m$, and capital $\{\hat{p}_{i2t}, \hat{q}_{i2tk}, \hat{w}_{i2tk}, \hat{r}_{i2t}\}$ where q_{i2tj} is the price of intermediate inputs, r_{i2t} the rental rate for land ; a set of expected lifetime returns to research and intermediate input production $\{\hat{V}_{it}^R, \hat{V}_{it}^P\}$; together with an allocation of consumption, final goods production, intermediate production, employment in research, employment in the intermediate sector, and usage of capital $\{\hat{c}_{i2t}, \hat{y}_{i2t}, \hat{x}_{i2tk}, \hat{H}_{it}^R, \hat{H}_{it}^P, \hat{k}_{i2t}\}$.

Given the structure of decision-making, general equilibrium can be solved for in two stages. First, we solve for equilibrium in the final goods, intermediate inputs, and land markets in period 2, for a given number of individuals entering research and intermediate input production in period 1 (H_{it}^R and H_{it}^P respectively) and for each of the two possible states of the world (successful and unsuccessful research). Second, having determined equilibrium period 2 payoffs in each state of the world as a function of H_{it}^R and H_{it}^P, we solve for the equilibrium number of individuals entering research and intermediate input production in period 1.

2.5.2. Period 2 Equilibrium: Unsuccessful Research

If research is unsuccessful, intermediate inputs are produced with the most productive existing technology m under conditions of perfect competition. Intermediate input producers receive a wage equal to their value of marginal product (VMP) with this technology,

[20] An alternative would be to assume that each individual entering research in country i innovates with probability λ_i, and, if more than one individual innovates, the patent is allocated randomly among the n_{it} researchers. In this case, the probability that any one researcher obtains the patent is $1/H_{it}^R\left[1-(1-\lambda_i)^{H_{it}^R}\right]$. This research technology exhibits a 'congestion effect', whereby, the larger the number of individuals entering research, the smaller the probability that anyone individual obtains the patent (see also Jones and Williams (1998)). The formulation in the text has the advantage that the probability of obtaining the patent is independent of the size of the research sector. However, all of the results in the paper are robust to considering the alternative formulation.

$$\underline{\hat{w}_{i2tm}} = \underline{\hat{q}_{i2tm}} = \alpha A_{2m(i)} \left(\frac{\underline{\hat{x}_{i2tm}}}{\hat{k}_{i2t}}\right)^{\alpha-1} = \alpha A_{2m(i)} \left(\frac{\underline{\hat{h}_{i2t}}}{\hat{k}_{i2t}}\right)^{\alpha-1} \tag{2.4}$$

where a bar underneath a variable indicates the state of the world where research is unsuccessful. There are zero equilibrium profits in intermediate input production. Period 2 demand for labour in the intermediate sector must, in equilibrium, equal supply, as endogenously determined by period 1 choices,

$$\underline{\hat{h}_{i2t}} = H_{it}^{P} \tag{2.5}$$

Equation (2.5) and the requirement that the capital market clears ($\hat{k}_{i2t} = K_i$) imply that period 2 final goods output is,[21]

$$\underline{\hat{y}_{i2t}} = A_{2m(i)} \left(H_{it}^{P}\right)^{\alpha} K_i^{1-\alpha} \tag{2.6}$$

2.5.3. Period 2 Equilibrium: Successful Research

A successful researcher receives a patent for the new technology $m+1$, and is the monopoly supplier of intermediate inputs produced using that technology. All bargaining power is assumed to reside with the researcher. She therefore chooses output and wages to maximize profits, subject to the derived demand curve for intermediate inputs, the production technology, the constraint that the wage offered to intermediate input producers is greater than or equal to the wage received with the previously most productive technology m, and the constraint that final goods production using intermediate inputs produced with technology $m+1$ is no more expensive than using those produced with technology m,

$$\max_{x_{i2t(m+1)}, w_{i2t(m+1)}} \left\{ q_{i2t(m+1)} . x_{i2t(m+1)} - w_{i2t(m+1)} h_{i2t} \right\} \tag{2.7}$$

[21] In the interests of tractability, we assume that the sector-specific factor of production (capital or land) cannot be accumulated over time. See Howitt and Aghion (1998) for an analysis of innovation and capital accumulation in a Schumpeterian model of endogenous growth.

$$
\text{subject to:} \quad
\begin{array}{l}
x_{i2t(m+1)} \geq 0 \\
x_{i2t(m+1)} = h_{i2t} \\
w_{i2t(m+1)} \geq w_{i2tm} \\
b_{i2t(m+1)} \left[q_{i2t(m+1)}, r_{i2t}\right] \leq b_{i2tm} \left[q_{i2tm}, r_{i2t}\right] \\
q_{i2t(m+1)} = \alpha A_{2(m(i)+1)} . x_{i2t(m+1)}^{\alpha-1} k_{i2t}^{1-\alpha}
\end{array}
$$

where $b_{i2tj}(\cdot)$ is the unit cost of producing final goods output using intermediate inputs of technology j, as a function of the price of intermediate inputs (q_{i2tj}) and the rental rate for land (r_{i2t}). This constrained optimization problem may be written as,

$$
\begin{aligned}
\max_{h_{i2t}, w_{i2t(m+1)}} \mathcal{L} = \alpha A_{2(m(i)+1)} k_{i2t}^{1-\alpha} . h_{i2t}^{\alpha} - w_{i2t(m+1)} h_{i2t} - \zeta_1 [w_{i2tm} - w_{i2t(m+1)}] \\
-\zeta_2 \left[b_{i2t(m+1)} \left[q_{i2t(m+1)}, r_{i2t}\right] - b_{i2tm} \left[q_{i2tm}, r_{i2t}\right] \right] - \zeta_3 [0 - h_{i2t}]
\end{aligned}
\tag{2.8}
$$

The first-order conditions are,

$$
\alpha^2 A_{2(m(i)+1)} . h_{i2t}^{\alpha-1} k_{i2t}^{1-\alpha} - w_{i2t(m+1)} - \zeta_2 . \frac{\partial b_{i2t(m+1)}(\cdot)}{\partial q_{i2t(m+1)}} . \frac{\partial q_{i2t(m+1)}}{\partial h_{i2t}} + \zeta_3 = 0 \tag{2.9}
$$

$$
-h_{i2t} + \zeta_1 = 0 \tag{2.10}
$$

$$
\zeta_1 \left[w_{i2tm} - w_{i2t(m+1)} \right] = 0 \tag{2.11}
$$

$$
\zeta_2 \left[b_{i2t(m+1)} \left[q_{i2t(m+1)}, r_{i2t}\right] - b_{i2tm} \left[q_{i2tk}, r_{i2t}\right] \right] = 0 \tag{2.12}
$$

$$
\zeta_3 [0 - h_{i2t}] = 0 \tag{2.13}
$$

The outside option of intermediate input producers in bargaining with the successful researcher is their value of marginal product (VMP) with the most productive existing technology m ($w_{i2tm} = q_{i2tm}$). From equation (2.7), profits from intermediate input production are monotonically decreasing in the wage ($w_{i2t(m+1)}$). Hence, in equilibrium, the holder of the patent to technology $m+1$ will pay intermediate input producers a wage no higher than their outside option ($w_{i2t(m+1)} = w_{i2tm}$ and $\zeta_1 > 0$ in equations (2.10) and (2.11)),

$$\overline{\hat{w}}_{i2t(m+1)} = \overline{\hat{w}}_{i2tm} = \overline{\hat{q}}_{i2tm} = \alpha A_{2m(i)} \left(\overline{\hat{h}}_{i2t}\right)^{\alpha-1} \left(\hat{k}_{i2t}\right)^{1-\alpha} \tag{2.14}$$

where a bar above a variable indicates the state of the world where research is successful.

If equilibrium output of intermediate inputs is positive ($\zeta_3 = 0$ in equation (2.9)), there are two possible equilibrium values for the price of intermediate inputs produced with technology $m+1$ depending upon whether this technology constitutes a 'drastic' or 'non-drastic' innovation. For simplicity, we consider the case of 'drastic' innovation, where it is cheaper for final goods producers to employ technology $m+1$ rather than m at the profit-maximizing monopoly price ($\zeta_2 = 0$ in equation (2.9)).[22] Equilibrium output of intermediate inputs produced with technology $m+1$ and equilibrium employment in the intermediate sector are,

$$\overline{\hat{x}}_{i2t(m+1)} = \overline{\hat{h}}_{i2t} = \left(\frac{\overline{\hat{w}}_{i2t(m+1)}}{\alpha^2 A_{2(m(i)+1)} \overline{\hat{k}}_{i2t}^{1-\alpha}}\right)^{1/(\alpha-1)} \tag{2.15}$$

Using equation (2.15) in the derived demand curve for intermediate inputs, the profit-maximizing monopoly price is simply,

$$\overline{\hat{q}}_{i2t(m+1)} = \frac{1}{\alpha}.\overline{\hat{w}}_{i2t(m+1)} = \frac{1}{\alpha}.\overline{\hat{w}}_{i2tm} \tag{2.16}$$

and equilibrium profits from intermediate input production are,

$$\overline{\hat{\pi}}_{i2t(m+1)} = \left(\frac{1}{\alpha} - 1\right).\overline{\hat{w}}_{i2tm}.\overline{\hat{h}}_{i2t} \tag{2.17}$$

Since $0 < \alpha < 1$, equilibrium profits from intermediate input production with technology $m+1$ are necessarily positive, and equilibrium output of intermediate inputs produced with a drastic innovation will indeed be strictly positive ($\zeta_3 = 0$ in equation (2.9)). Equilibrium period 2 demand for labour in the intermediate sector must again equal supply as endogenously determined by period 1 choices,

$$\overline{\hat{h}}_{i2t} = H_t^P \tag{2.18}$$

[22] As in Aghion and Howitt (1992), the condition for an innovation to be drastic is $\gamma > \alpha^{-\alpha}$, and is derived from the Cobb-Douglas unit cost function. All of the results that follow continue to hold in the case of non-drastic innovation.

Equation (2.18) and the requirement that the land market clear ($\hat{k}_{i2t} = K_i$) imply that period 2 final goods output is,

$$\overline{y}_{i2t} = A_{2(m(i)+1)}.\left(H_{it}^P\right)^{\alpha} K_i^{1-\alpha} \tag{2.19}$$

2.5.4. Period 1 Equilibrium Choice Between Research and Intermediate Production

In an equilibrium with positive levels of research, we require the expected lifetime return from research ($\hat{V}_{it}^R$) to equal the corresponding expected lifetime return from intermediate production ($\hat{V}_{it}^P$),

$$\hat{V}_{it}^R = \hat{V}_{it}^P \tag{2.20}$$

With probability λ_i an individual researcher obtains the patent to the next technology $m+1$ and enjoys an equilibrium flow of profits equal to (2.17). With probability $(1-\lambda_i)$, she fails to obtain the patent and receives zero period 2 returns from research.[23] The expected lifetime return from research is thus,

$$\hat{V}_{it(m+1)}^R = \lambda_i \left(\frac{1-\alpha}{\alpha}\right) \hat{w}_{i2tm} \hat{H}_{it}^P \tag{2.21}$$

¿From the analysis of the previous subsections, the equilibrium period 2 wage of intermediate input producers is independent of whether research is successful in period 1 and equals their value of marginal product (VMP) with technology m. The expected lifetime return from intermediate input production is thus,

$$\hat{V}_{itm}^P = \hat{w}_{i2tm} \tag{2.22}$$

In equilibrium, the number of intermediate input producers equals the supply of workers minus those who choose to enter the research sector,

$$\hat{H}_{it}^P = H_i - \hat{H}_{it}^R \tag{2.23}$$

[23] Although the researcher receives a period 2 income of $\hat{r}_{i2t}.(K_i/H_i)$ from her endowment of capital.

Using equations (2.20), (2.21), (2.22), and (2.23), the requirement that the expected lifetime return from research equals the expected lifetime return from intermediate production becomes,

$$1 = \lambda_i \left(\frac{1-\alpha}{\alpha}\right)(H_i - \hat{H}_i^R) \tag{2.24}$$

For parameter values such that $\lambda_i\left(\frac{1-\alpha}{\alpha}\right)H_i > 1$, equation (2.24) defines a unique equilibrium level of research employment ($0 < \hat{H}_i^R < H_i$), which is shown diagrammatically in Figure 2. The left and right-hand sides of equation (2.24) may be interpreted as the private marginal cost and marginal benefit of research respectively. The relationship between the parameters of the model and equilibrium research employment is directly analogous to Aghion and Howitt (1992).[24] From the final goods production technology (2.2), the expected rate of TFP growth between generations is simply,

$$\mathsf{E}_{t-1} \ln\left(\frac{A_{i2t}}{A_{i2t-1}}\right) = \lambda \hat{H}_i^R . \ln\gamma \tag{2.25}$$

which is increasing in the size of innovations (γ), the probability of research success (λ), and equilibrium research employment ($\hat{H}_i^R$).

<Figure 2 about here>

3. Technological Convergence and the Two Faces of R&D

3.1. Introduction

The overlapping generations version of Aghion and Howitt (1992) will form part of a single unified framework that integrates Schumpeterian models of endogenous growth, the microeconometric literature on R&D and productivity, and empirical analyses of productivity convergence. While the previous section allows for cross-country differences in levels of TFP ($A_{2m(i)}$), it does not consider the possibility of technology spillovers. It is plausible that some technology transfer may occur independently of investments in formal R&D. At the same time, the literature on absorptive capacity

[24] As currently specified, the model exhibits a 'scale effect', whereby increases in the supply of labour H_i lead to higher equilibrium employment in research. It is relatively straightforward to modify the model to eliminate this scale effect (see, for example, Dinopoulos and Thompson (1998), Howitt (1999), and Segerstrom (1998)). Eaton *et al.* (1998) argue that one of the reasons why R&D investment in Europe has historically been lower than in the US (despite a higher estimated private rate of return) is the segmentation of national markets.

suggests that R&D plays an important role in the acquisition of tacit knowledge and the imitation of others' discoveries. The model presented below captures both features.

3.2. Technological Convergence

The main structure of the model remains exactly as before. At the beginning of period one, agents choose whether to engage in research or intermediate production. Research takes one period and all research uncertainty is resolved at the end of period 1. If an economy lies behind the technological frontier, technology transfer also occurs during period 1. Independent of whether research is successful or unsuccessful in period 1, the quality or productivity of intermediate inputs rises by a proportion $Q_i(A_{2m(F)}/A_{2m(i)})$. Thus, if research is unsuccessful,

$$\underline{A_{2(m(i)+1)}} = Q_i \left(\frac{A_{2m(F)}}{A_{2m(i)}} \right) .A_{2m(i)} \tag{3.1}$$

where F indicates the economy with the highest level of TFP (the technological frontier). $Q_i(\cdot)$ satisfies the following conditions,

$$Q_i(1) = 1, \qquad Q_i'(\cdot) > 0, \qquad Q_i''(\cdot) < 0, \qquad \forall\ i$$

and, for simplicity, we consider the constant elasticity functional form,

$$Q_i \left(\frac{A_{2m(F)}}{A_{2m(i)}} \right) = \left(\frac{A_{2m(F)}}{A_{2m(i)}} \right)^{\mu_i}, \qquad 0 < \mu_i < 1, \qquad \forall\ i$$

where μ_i corresponds to the speed of autonomous technology transfer (independent of R&D). We allow this parameter to potentially vary across countries again as a function, for example, of government policy and institutions.

3.3. R&D and Absorptive Capacity

If research is successful, the quality or productivity of intermediate inputs is raised by a proportion $\Gamma > 1$ over the level that would otherwise be achieved through technology transfer alone. To capture R&D's role in promoting 'absorptive capacity' and facilitating the transfer of technology, we follow Aghion and Howitt (1998) and Howitt (2000) in allowing the size of innovations Γ to be a function of a country's distance behind the technological frontier,

$$\Gamma = \Gamma_i \left(\frac{A_{2m(F)}}{A_{2m(i)}} \right), \qquad \Gamma_i(1) > 1, \qquad \Gamma_i'(\cdot) > 0, \qquad \Gamma_i''(\cdot) < 0, \quad \forall\, i$$

where we again consider the constant elasticity functional form,

$$\Gamma_i \left(\frac{A_{2m(F)}}{A_{2m(i)}} \right) = \gamma . \left(\frac{A_{2m(F)}}{A_{2m(i)}} \right)^{\phi_i}, \qquad \gamma > 1, \quad 0 < \phi_i < 1, \quad \forall\, i$$

In the frontier country with the highest TFP level ($A_{2m(i)} = A_{2m(F)}$), the size of innovations is $\gamma > 1$, exactly as in the previous Section. In non-frontier countries ($A_{2m(i)} < A_{2m(F)}$), R&D activity also facilitates the assimilation of ideas from the technological frontier, and the size of innovations is, as a result, increased. The further a country lies behind the technological frontier, the greater the potential for R&D-based technology transfer, and the greater the size of innovations when they occur.[25] The parameter ϕ_i determines the speed with which the size of innovations varies with the technological gap, and is again allowed to vary across countries as a function of government policy and institutions. Thus, if research is successful in period 1, the quality or productivity of intermediate inputs is given by,

$$\overline{A}_{2(m(i)+1)} = \gamma . \left(\frac{A_{2m(F)}}{A_{2m(i)}} \right)^{\phi_i + \mu_i} A_{2m(i)} \tag{3.2}$$

3.4. General Equilibrium

The determination of general equilibrium remains exactly as in the previous Section. In an equilibrium with positive research, we require the expected lifetime return from research ($\hat{V}_{it}^R$) to equal the corresponding expected lifetime return from intermediate production ($\hat{V}_{it}^P$),

$$\hat{V}_{it}^R = \hat{V}_{it}^P \tag{3.3}$$

$$1 = \lambda_i \left(\frac{1-\alpha}{\alpha} \right) (H_i - \hat{H}_i^R) \tag{3.4}$$

[25] Although being behind the technological frontier increases the size of innovations, the magnitude of the increase in the size of innovations diminishes as one moves further and further behind the frontier: $\Gamma_i''(\cdot) < 0$.

The equilibrium value of research employment is exactly as before. The equilibrium period 2 wage paid to intermediate input producers is again independent of whether research is successful and equals,

$$\hat{w}_{i2t(m(i)+1)} = \alpha \left(\frac{A_{2m(F)}}{A_{2m(i)}} \right)^{\mu_i} A_{2m(i)} \left(H_i - \hat{H}_i^R \right)^{\alpha-1} (K_i)^{1-\alpha} \tag{3.5}$$

¿From the final goods production technology (2.2), the expected rate of TFP growth between generations is now,

$$\mathsf{E}_{t-1} \ln \left(\frac{A_{i2(m+1)t}}{A_{i2m(t-1)}} \right) = \underbrace{\lambda_i \hat{H}_i^R \ln \gamma}_{\text{term 1}} + \underbrace{\mu_i \ln \left(\frac{A_{2m(F)(t-1)}}{A_{2m(i)(t-1)}} \right)}_{\text{term 2}} + \underbrace{\phi_i \lambda_i \hat{H}_i^R \ln \left(\frac{A_{2m(F)(t-1)}}{A_{2m(i)(t-1)}} \right)}_{\text{term 3}} \tag{3.6}$$

The equation for TFP growth includes a term in the level of R&D activity (Term 1, the direct R&D effect), a term in distance from the frontier capturing technology transfer that occurs independently of R&D activity (Term 2, autonomous technological catchup), and an interaction term between R&D and distance from the frontier that captures R&D's role in promoting absorptive capacity (Term 3, absorptive capacity). The microeconometric literature on R&D and productivity focuses on the first of these three terms, excluding technology transfer and absorptive capacity as potential sources of productivity growth.[26] In contrast, the empirical literature on industry-level productivity convergence focuses on the second term, and devotes little attention to R&D as a source of productivity growth.[27] The structural model presented above suggests a role for both sets of considerations, plus an interaction term between R&D and distance from the technological frontier, capturing R&D-based absorptive capacity.

3.5. Social Rate of Return to R&D and Steady-state Levels of Relative TFP

Equation (3.6) characterizes TFP growth in all countries $i \in \{1, ..., N\}$. In the frontier country with the highest level of TFP ($i = F$), this equation simplifies to,

$$\mathsf{E}_{t-1} \ln \left(\frac{A_{F2(m+1)t}}{A_{F2m(t-1)}} \right) = \lambda_F \hat{H}_F^R \ln \gamma \tag{3.7}$$

[26] See, for example, the discussion in Mohnen (1996).

[27] Some of the most influential contributions in this literature include Bernard and Jones (1996a), (1996b), Dollar and Wolff (1994), and Jorgenson and Kuroda (1990).

In the empirical productivity literature, regressions of TFP growth on measures of R&D activity are widely used to estimate the social rate of return to R&D. The coefficients on R&D in equations (3.6) and (3.7) are $\rho_i \equiv \lambda_i \left[\ln \gamma + \phi_i \ln(A_{2m(F)(t-1)}/A_{2m(i)(t-1)})\right]$ and $\rho_F \equiv \lambda_F \ln \gamma$. Controlling for the values of λ_i and ϕ_i, the model suggests that the social rate of return to R&D is higher in non-frontier countries, where R&D may raise rates of TFP growth through its role in promoting absorptive capacity. This idea receives empirical support in the results presented below and in independent research using a computable general equilibrium model by Eaton *et al.* (1998). At first sight, this suggests that the incentive to invest in R&D should be greater in non-frontier countries. However, the social rate of return to R&D obtained from a TFP growth regression is not a measure of private incentives to engage in R&D (which are determined according to equation (3.4)). Furthermore, the above conclusion concerning social rates of return only holds for the same values of λ_i and ϕ_i: in equilibrium, non-frontier countries may lie behind the technological frontier precisely because they have low values of λ_i and ϕ_i.

In steady-state equilibrium, whichever country has the higher value of $\lambda_i \hat{H}_i^R$ will become the technological frontier. Combining equations (3.6) and (3.7), the evolution of TFP in all other countries i relative to the frontier is governed by the difference equation,

$$\mathsf{E}_{t-1} \triangle \ln \tilde{A}_{2t} = \left(\lambda_F \hat{H}_F^R - \lambda_i \hat{H}_i^R\right) \ln \gamma - \left(\lambda_i \hat{H}_i^R \phi_i + \mu_i\right) \ln \left(\tilde{A}_{2(t-1)}\right) \tag{3.8}$$

where $\tilde{A}_{2t} = A_{2m(F)t}/A_{2m(i)t}$, the difference operator $\triangle$ denotes the change between generations $t-1$ and t, and where, to simplify notation, we suppress the implicit dependence on $m(i)$. We define steady-state relative TFP in country i as the value for relative TFP such that expected TFP growth in country i equals that in the frontier. At this value for relative TFP, the country is an equilibrium distance behind the frontier such that expected TFP growth from innovation and technology transfer exactly equals expected TFP growth in the frontier from innovation alone. From equation (3.8), the steady-state level of relative TFP in a non-frontier country i is given by,

$$\ln \tilde{A}_{2t}^{*} = \frac{\left(\lambda_F \hat{H}_F^R - \lambda_i \hat{H}_i^R\right) \ln \gamma}{\left(\lambda_i \hat{H}_i^R \phi_i + \mu_i\right)} \tag{3.9}$$

Steady-state relative TFP depends on institutions and government policy which affect the productivity of research (λ_i, λ_F), the determinants of equilibrium research employment ($\hat{H}_i^R$, $\hat{H}_F^R$), the size of innovations in the frontier (γ), and the speed of autonomous and absorptive capacity-induced technology transfer (μ_i and ϕ_i).

4. Many Final Goods Sectors

This section extends the analysis to incorporate multiple final goods sectors indexed by $j \in \{1, ..., J\}$. The lifetime utility of a representative consumer-worker in generation t of country i is assumed to depend on a second-period consumption index (C_{i2t}) defined over consumption of the J final goods. For simplicity, we consider the case where the outputs of each sector are perfect substitutes, and lifetime utility takes the form,[28]

$$U_{it} = C_{i2t} = \sum_{j=1}^{J} c_{i2jt} \tag{4.1}$$

Units of each final good are homogeneous, and we assume that all final goods are tradeable across countries at zero transport cost. From the representative consumer's constrained maximization problem,

$$p_{i2jt} = \frac{1}{\zeta_i}, \qquad \forall\ i, j \tag{4.2}$$

where ζ_i is the marginal utility of income. Preferences are identical in all countries and utility is linear in the consumption of each good. The marginal utility of income is thus the same in all countries, and we choose this for the numeraire, so that $p_{i2jt} = 1$ for all i and j. The production technology is directly analogous to equation (2.2). Each final goods sector j has its own intermediate sector. Final goods output is produced using intermediate inputs and capital,

$$y_{i2jt} = A_{i2jt}.x_{i2jt}^{\alpha} k_{i2jt}^{1-\alpha}, \qquad 0 < \alpha < 1 \tag{4.3}$$

Capital is used solely in the production of final goods, but is perfectly mobile across all sectors j.

[28]See Aghion and Howitt (1998) for an analogous formulation with multiple intermediate goods sectors in the standard quality ladder model of growth.

At the beginning of period 1, workers inherit stocks of knowledge in each sector from the previous generation, and decide whether to engage in research or intermediate input production in a sector j. We denote the number of individuals entering either research or intermediate production in sector j by $H_{ijt} = H^R_{ijt} + H^P_{ijt}$. General equilibrium requires that the following conditions are satisfied. First, in an equilibrium with positive research, we require that the H_{ijt} agents in sector j are indifferent between research and intermediate production. This no-arbitrage condition takes exactly the same form as before,

$$1 = \lambda_{ij} \left(\frac{1-\alpha}{\alpha} \right) .(H_{ijt} - \hat{H}^R_{ijt}) \tag{4.4}$$

where the productivity of research (λ) is allowed to vary both across sectors within a country and across countries. For any given total allocation of labour to sector j (H_{ijt}), this equation determines equilibrium research employment (and hence equilibrium employment in intermediate production). Second, workers must be indifferent between producing intermediate inputs in sector j and all other sectors $l \neq j$,

$$w_{i2jt} = w_{i2lt}, \qquad \forall j, l \tag{4.5}$$

where the period 2 wage is determined exactly as before,

$$\hat{w}_{i2jt(m+1)} = \alpha \left(\frac{A_{2m(Fj)t}}{A_{2m(ij)t}} \right)^{\mu_{ij}} A_{2m(ij)t} \left(H_{ijt} - \hat{H}^R_{ijt} \right)^{\alpha-1} \left(\hat{k}_{i2jt} \right)^{1-\alpha} \tag{4.6}$$

and we now allow the speed of autonomous technology transfer (μ) to vary across both countries and industries. Third, we require that the rental rate for capital is the same in sector j and all other sectors $l \neq j$,

$$\hat{r}_{i2jt} = \hat{r}_{i2lt} \qquad \forall j, l \tag{4.7}$$

where, with a perfectly competitive final goods sector, the equilibrium rental rate for capital equals its (common) value marginal product (VMP) in each sector j. Fourth, the markets for labour and capital must clear,

$$\sum_{j=1}^{J} \hat{H}_{ijt} = H_i \tag{4.8}$$

$$\sum_{j=1}^{J} \hat{k}_{i2jt} = K_i \tag{4.9}$$

Taking equations (4.4), (4.5), and (4.7) for each sector j, and combining them with the market clearing conditions (4.8) and (4.9), we obtain a system of $3J+2$ equations in $3J$ unknowns $\{\hat{H}_{ijt}, \hat{H}^R_{ijt}, \hat{k}_{i2jt}\}$. Given the inherited stocks of knowledge across sectors in each country i, we may solve for equilibrium research employment in sector j, the total number of workers engaged in either research or intermediate production in sector j, and the equilibrium employment of capital in sector j. It would be straightforward to simulate the model for specific parameter values. The equation for TFP growth in sector j of country i is directly analogous to that above,

$$\begin{aligned}\mathsf{E}_{t-1} \ln\left(\frac{A_{i2(m+1)jt}}{A_{i2mj(t-1)}}\right) =& \underbrace{\lambda_{ij}\hat{H}^R_{ij(t-1)} \ln\gamma}_{\text{term 1}} + \underbrace{\mu_{ij} \ln\left(\frac{A_{2m(F)j(t-1)}}{A_{2m(i)j(t-1)}}\right)}_{\text{term 2}} \\ &+ \underbrace{\phi_{ij}\lambda_{ij}\hat{H}^R_{ij(t-1)} \ln\left(\frac{A_{2m(F)j(t-1)}}{A_{2m(i)j(t-1)}}\right)}_{\text{term 3}}\end{aligned} \tag{4.10}$$

Again here we have an equation for TFP growth that includes a term in the level of R&D activity (Term 1, the direct R&D effect), a term in distance from the frontier capturing technology transfer that occurs independently of R&D activity (Term 2, autonomous technological catchup), and an interaction term between R&D and distance from the frontier that captures R&D's role in promoting absorptive capacity (Term 3, absorptive capacity).

5. Empirical Evidence

The expression for industry-level TFP growth in equation (4.10) takes the same form as the reduced-form econometric equations estimated in Cameron (1996), Cameron, Proudman, and Redding (1998), and Griffith, Redding, and Van Reenen (2000). The general equilibrium model of endogenous innovation and growth of previous sections provides microeconomic foundations for this reduced-form equation. The estimated coefficients can be directly related to the structural parameters of the model. The theory has clear predictions that are empirically falsifiable. In particular, a role for R&D in promoting absorptive capacity implies a positive and statistically significant coefficient on the R&D interaction term ($\phi_{ij}\lambda_{ij} > 0$).

Table 1 summarizes the empirical results in Griffith, Redding, and Van Reenen (2000) from estimating the relationship in equation (4.10) using industry-level data from 12 OECD countries since 1974. The exact equation estimated is,

$$\begin{aligned} \triangle \ln A_{ijt} = \eta_{ij} + \nu \left(\tfrac{R}{Y}\right)_{ijt-1} + \beta \triangle \ln A_{Fjt} + \delta_1 \ln \left(\tfrac{A_F}{A_i}\right)_{jt-1} \\ +\delta_2 \left[\left(\tfrac{R_i}{Y_i}\right) \ln \left(\tfrac{A_F}{A_i}\right)\right]_{jt-1} + \theta' X_{ijt-1} + T_t + \varepsilon_{ijt}. \end{aligned} \tag{5.1}$$

As is conventional in the microeconometric literature, R&D activity is measured by the ratio of R&D expenditure to value-added (R/Y). TFP growth and TFP relative to the frontier are measured with superlative index numbers.[29] The TFP measures used control for cross-country differences in hours worked and for country-industry variation in labour quality using data on employment and wage bill shares of non-production workers.[30] The specification in equation (5.1) includes a full set of year dummies (T_t) to control for common macroeconomic shocks. Estimation is by within groups, and the parameters of interest are therefore identified using deviations from country-industry means.

The presence of the country-industry fixed effect (η_{ij}) controls for unobserved heterogeneity in the determinants of TFP growth, which is allowed to be correlated with the explanatory variables. The country-industry fixed effect and common slope coefficients in (5.1) also place more structure on the way in which the parameters λ_{ij}, μ_{ij}, and $\phi_{ij}\lambda_{ij}$ vary across countries and industries relative to equation (4.10). In the discussion of the theoretical model, variation in these parameters was linked to cross-country differences in government policy and institutions. These are slow to change over time and, under an appropriate parameter normalization, can be captured in the fixed effect.[31] The coefficient on R&D varies across country-industries in (5.1), but in a systematic way related to distance

[29]See Caves *et al.* (1982a), (1982b).

[30]As further robustness tests, Griffith, Redding, and Van Reenen (2000) also control for differences across countries and industries in the degree of imperfect competition, the extent of capacity utilization, and in the relative prices of the output of different sectors (industry-specific Purchasing Power Parities (PPPs)).

[31]The within groups transformation means that the parameters of interest are identified using deviations from country-industry means. In moving from (4.10) to (5.1), we assume $\lambda_{ij} = \nu + \psi_{ij}/((R/Y)_{ijt-1} - \overline{(R/Y)}_{ij})$, where ψ_{ij} is captured in the fixed effect (η_{ij}) and the upper bar denotes a mean across years.

from the technological frontier ($\rho_{ijt-1} \equiv \nu + \delta_2 \ln(A_F/A_i)_{jt-1}$). Griffith, Redding, and Van Reenen (2000) also experiment with allowing more general forms of parameter heterogeneity, and compare the results with those from estimating (5.1). X denotes a vector of potential control variables, thought to be important determinants of TFP growth in addition to R&D. The main control variables considered are human capital (following the country-level work of Benhabib and Spiegel (1994)) and (in some specifications) international trade (following the country-level literature on trade and growth). Finally, the term in contemporaneous TFP growth in the frontier ($\triangle \ln A_F$) allows for a more general econometric relationship between TFP in non-frontier and frontier countries.[32]

Column (1) summarizes the results of estimating the basic R&D specification using within groups (see Griffith, Redding, and Van Reenen (2000) for further details). The estimated values of all coefficients take the same sign as expected from the theory and all are statistically significant at the 5% level. The estimated coefficient on the R&D level term can be interpreted as the social rate of return to R&D in the frontier ($A_i = A_F$), and is broadly consistent with existing empirical estimates (see, for example, Jones and Williams (1998)). The positive and statistically significant coefficient on the R&D interaction suggests an important role for R&D in promoting absorptive capacity. In so far as many existing empirical studies of R&D and productivity focus on the US (typically the frontier in our data), they will underestimate the social rate of return to R&D in non-frontier countries, where R&D also promotes productivity growth through the assimilation of technologies from more advanced countries. The positive and statistically significant coefficient on the relative TFP term suggests a role for autonomous technology transfer independent of R&D activity. Column (2) establishes the robustness of these results to treating relative TFP at $t-1$ as endogenous and instrumenting with lagged values of the explanatory variables. The Sargan test statistic implies that we are unable to reject the null hypothesis of the orthogonality of the residuals and the excluded exogenous variables at the 5% level. The instruments are highly statistically significant in the first-stage regression. Conditional on the covariates, we find no evidence of serial correlation in the residuals, as is required for lagged values of the explanatory variables to be valid instruments.

[32] The specification considered in equation (5.1) is consistent with an ADL(1,1) cointegrating relationship between non-frontier and frontier TFP. See Griffith, Redding, and Van Reenen (2000) for further discussion.

Table 1: TFP growth, R&D, and Absorptive Capacity

ΔTFP_{ijt} Estimation		(1) Within Groups	(2) IV	(3) Within Groups	(4) IV
R/Y_{ijt-1}	ν	0.433	0.382	0.427	0.383
		0.179	*0.189*	*0.188*	*0.183*
ΔTFP_{Fjt}	β	0.124	0.130	0.121	0.128
		0.030	*0.031*	*0.030*	*0.031*
$RTFP_{ijt-1}$	δ_1	0.068	0.072	0.024	0.034
		0.016	*0.020*	*0.021*	*0.025*
$(RTFP * R/Y)_{ijt-1}$	δ_2	1.00	1.345	0.815	1.14
		0.344	*0.398*	*0.348*	*0.404*
H_{it-1}	θ_1		-	0.225	0.237
				0.124	*0.124*
$(RTFP * H)_{ijt-1}$	θ_2		-	0.459	-0.432
				0.136	*0.176*
Year dummies		yes	yes	yes	yes
Country-industry fixed effect		yes	yes	yes	yes
Serial Correlation		0.185	0.969	0.318	1.060
Sargan (p-value)		-	0.072	-	0.086

Notes: this table summarizes empirical results from Griffith, Redding, and Van Reenen (2000); sample contains 1801 observations from 1974-1990; numbers in italics coefficients are robust standard errors; all regressions include full set of time dummies and full set of country-industry interactions (i.e. within groups estimator); observations are weighted using industry shares of total manufacturing employment in 1970; ΔTFP is logarithmic growth in TFP in country i; RTFP is relative level of TFP defined as ln(TFP in frontier) minus ln(TFP in country i); R/Y is R&D intensity; H is human capital; serial correlation is LM test for first order serial correlation, distributed N(0,1) under null; Sargan is test for validity of overidentifying restrictions; TFP measure is adjusted for country-industry differences in the skill composition of the workforce and for cross-country differences in hours worked; exogenous variables included in column (2) are $\Delta TFP_{Fjt}, RTFP_{ijt-2}, RTFP_{ijt-3}, R/Y_{ijt-1}, (RTFP_{ijt-2} * R/Y_{ijt-1}), (RTFP_{ijt-3} * R/Y_{ijt-1})$; plus in column (4) $H_{ijt-1}, (RTFP_{ijt-2} * H_{ijt-1}), (RTFP_{ijt-3} * H_{ijt-1})$.

Columns (3) and (4) summarize the results of a robustness test, including information on educational attainment from Barro and Lee (1994) as a control variable. The human capital measure is defined as the percentage of the population who have attained higher education (see Griffith, Redding, and Van Reenen (2000) for further details). Both the R&D and the human capital level terms are positively signed and statistically significant at the 5% level, as are the R&D and human capital interaction terms. This suggests an important role for both R&D and human capital in promoting absorptive capacity. The estimated coefficient on the relative TFP term is no longer statistically significant at the 5% level, suggesting that human capital, R&D, and permanent factors captured in the country-industry fixed effect fully determine a country's ability to assimilate technologies from more advanced countries. These results are confirmed in Column (4), where we treat relative TFP at $t-1$ as endogenous and instrument with lagged values of the explanatory variables. The Sargan test statistic again implies that we are unable to reject the null hypothesis of the orthogonality of the residuals and the excluded exogenous variables at the 5% level. The instruments are highly statistically significant in the first-stage regression. Conditional on the covariates, we again find no evidence of serial correlation in the residuals.

The empirical results from estimating the reduced-form equation (5.1) provide direct support for the predictions of the theoretical model. This reduced-form equation has a clear microeconomic foundation in a structural Schumpeterian model of endogenous innovation and growth. The empirical finding that R&D promotes absorptive capacity finds independent support in the firm-level results using patents and profitability in Jaffe (1986) and in the country-level results using a computable general equilibrium model in Eaton *et al.* (1998).

6. Conclusions

The paper has presented a single unified model that integrates the theoretical literature on Schumpeterian endogenous growth, the microeconometric literature on R&D and productivity, and the empirical literature on productivity convergence. Starting from a structural model of endogenous innovation and growth following Aghion and Howitt (1992, 1998), we provide microeconomic foundations for a reduced-form equation for rates of Total Factor Productivity (TFP) growth which has been estimated empirically at the industry-level. The model has clear theoretical predictions which are empirically falsifiable, and the values of the estimated coefficients in the reduced-form equation can be directly related to the structural parameters of the model.

Empirical results were presented in support of this econometric specification. R&D was found to play an important role in promoting the absorption or imitation of discoveries from more technological advanced countries, a role which has been termed the 'second face of R&D'. These empirical results are robust across a wide range of different econometric specifications, for a number of different measures of TFP, and after including a number of different control variables. The existing microeconometric literature on R&D and productivity underestimates the social rate of return to R&D in non-frontier countries, in so far as excludes the second face of R&D. The model sheds light on the determinants of long-run productivity growth and long-run levels of relative productivity at the industry-level. The analysis thus contributes to the ongoing policy debate concerning the social return to R&D and explanations for cross-country differences in productivity levels.

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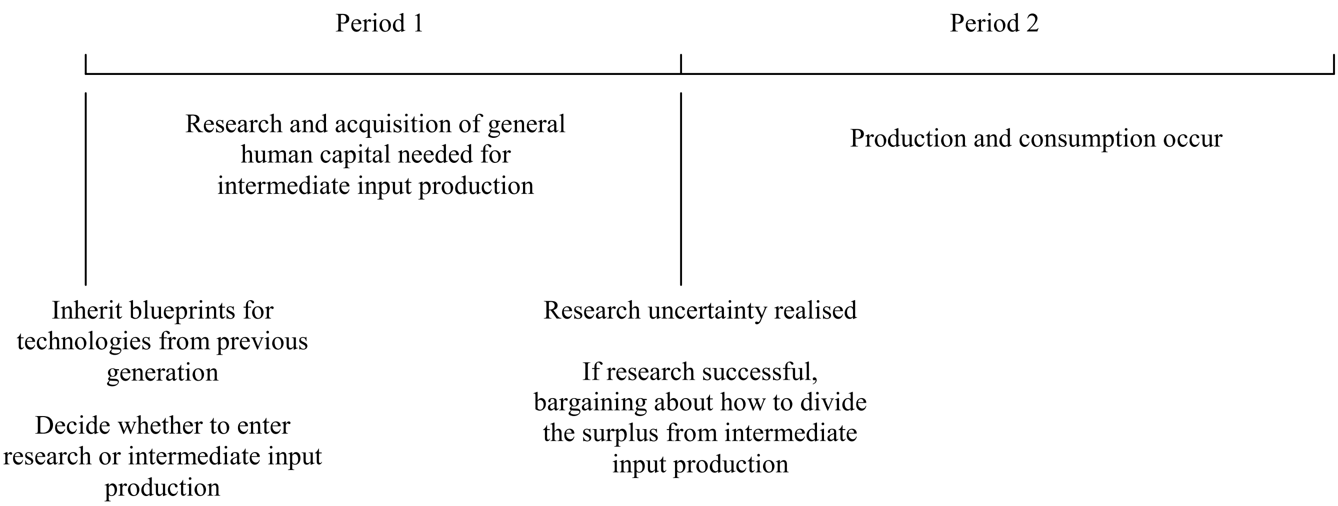


Figure 1: The Timing of Decisions

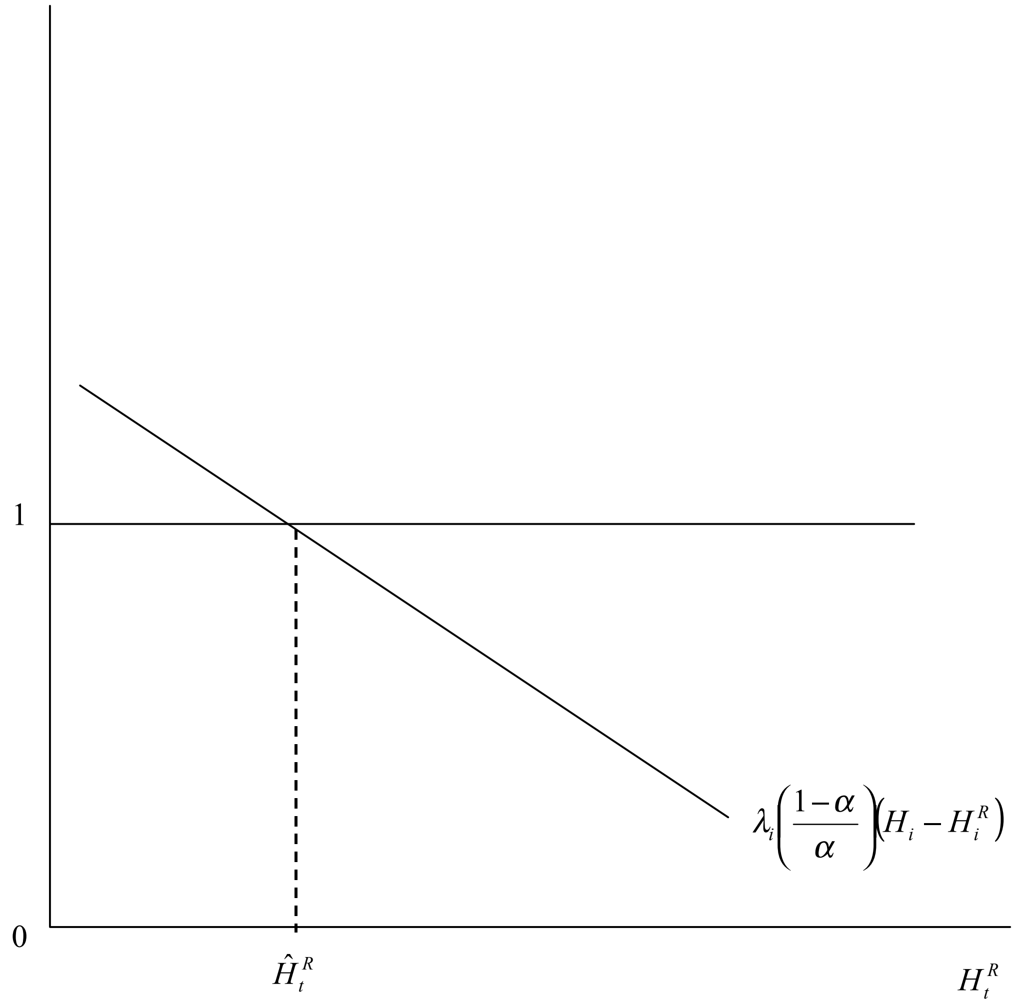
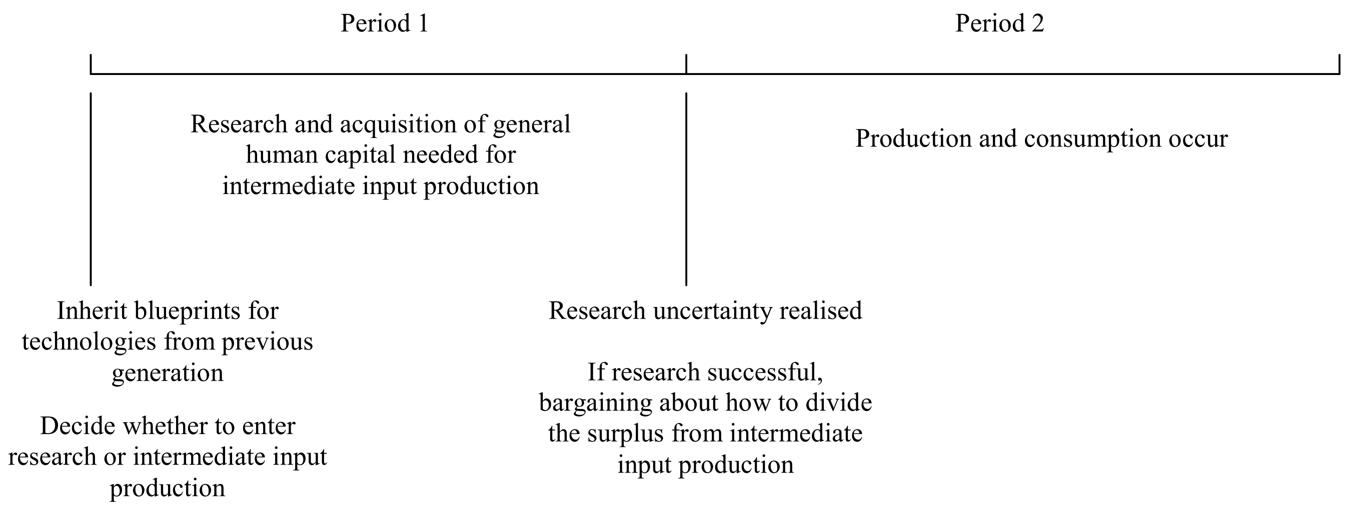


Figure 2: equilibrium research employment



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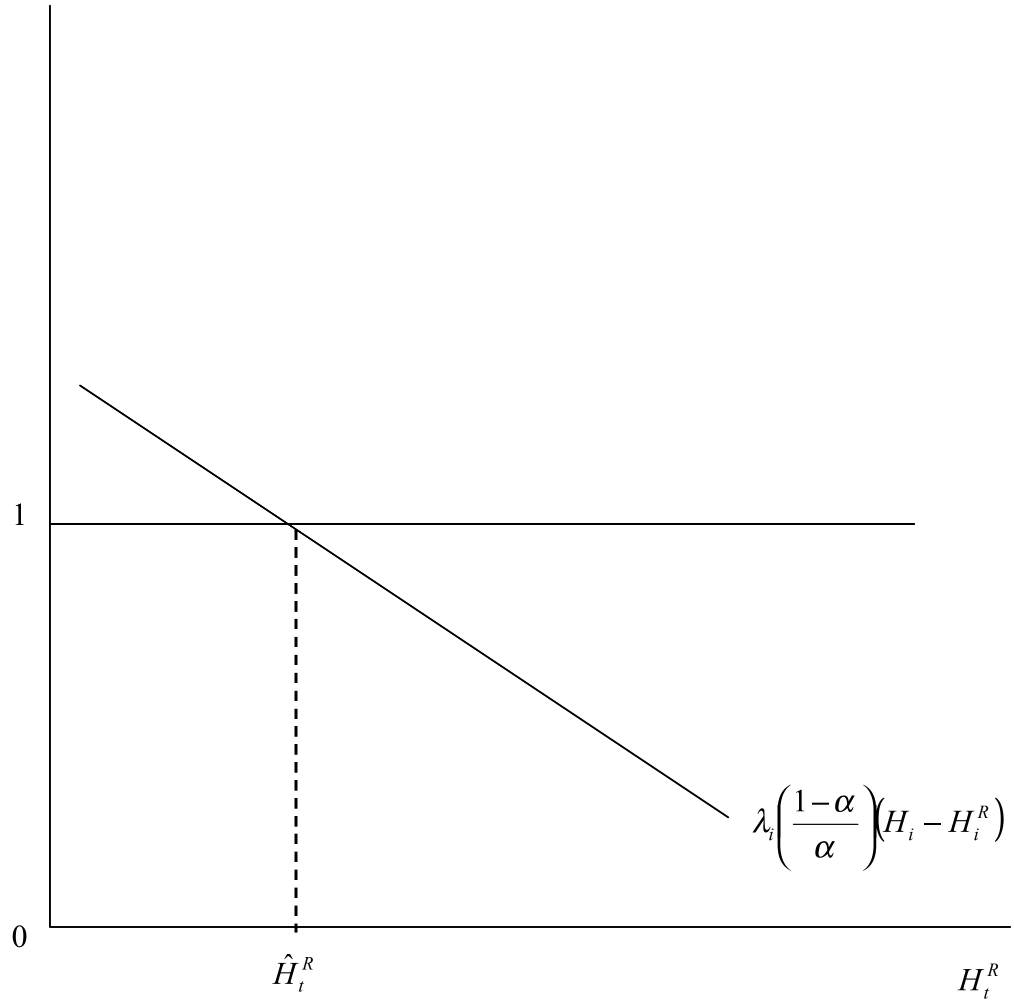

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