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R&D and absorptive capacity : theory and empirical evidence

R&D and Absorptive Capacity: Theory and Empirical Evidence[*]

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Abstract

This paper presents a single unified framework that integrates the theoretical literature on Schumpeterian endogenous growth and major strands of the empirical literatures on R&D, productivity growth, and productivity convergence. Starting from a structural model of endogenous growth following Aghion and Howitt (1992), (1998), we provide microeconomic foundations for the reduced-form equations for Total Factor Productivity (TFP) growth frequently estimated empirically using industry-level data. R&D affects both innovation and the assimilation of others' discoveries ('absorptive capacity'). Long-run cross-country differences in productivity emerge endogenously, and the analysis implies that many existing studies underestimate R&D's social rate of return by neglecting absorptive capacity.

JEL CLASSIFICATION: O10, O30, O47

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

I Introduction

A frequent theme in the literatures on the history and microeconomics of technology is that some knowledge is 'tacit', difficult to codify in manuals and textbooks, and hard to acquire without direct investigation. Only by actively engaging in research in a particular intellectual or technological field, does one acquire such tacit knowledge and become able to easily understand and assimilate the discoveries of others. An example, cited by Arrow (1969), is the jet engine: when plans were supplied by Britain to America during the Second World War, it took ten months for these plans to be redrawn to conform to American usage. This paper shows how R&D's role in promoting 'absorptive capacity' (the 'second face of R&D') can be incorporated into a general equilibrium model of endogenous innovation and growth following Aghion and Howitt (1992), (1998) and how the resulting theoretical framework can be directly related to the empirical literatures on productivity growth and convergence. We construct a single unified framework that integrates theoretical research on endogenous growth, micro-econometric work on R&D and productivity growth, and empirical findings of productivity convergence.

The theoretical model of endogenous growth provides microeconomic foundations for the reduced-form equations for Total Factor Productivity (TFP) growth frequently estimated at the industry-level in the productivity growth and convergence literatures. The TFP growth equation includes R&D-based innovation, the potential for technology transfer, and a role for R&D in promoting absorptive capacity. Much of the existing empirical literature focuses on only one or two of these mechanisms. We review empirical evidence suggesting that all three effects are statistically and economically important. The values of the estimated coefficients in the reduced-form can be directly related to structural parameters of the model, and the theory's predictions are potentially empirically falsifiable. The model has predictions for long-run equilibrium levels of relative TFP, and is relevant for the recent debate concerning

productivity differences across countries and industries. A central implication of our analysis is that many existing empirical studies underestimate the social rate of return to R&D because they have neglecting R&D's role in the assimilation of new technologies,.

The paper relates to three main existing literatures. First, the theoretical literature on Schumpeterian models of endogenous growth emphasizes the non-rivalrous and partially excludable nature of knowledge.[1] 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. 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 provide microeconomic foundations for the reduced-form TFP growth equations estimated in the empirical literature.

Second, a substantial body of empirical work has examined the relationship between R&D and productivity growth at the firm and industry-level. Much of this empirical research is concerned with R&D-based innovation, and the conventional approach is to regress TFP growth on measures of R&D activity.[2] An important strand of work examines R&D knowledge spillovers across industries, countries, and regions.[3] In each case, the analysis is concerned with the effect of *other* agents' R&D on own productivity. The discussion above suggests that *own* R&D may play an important role in the absorption of the fruits of others' R&D investments. Empirical

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[1] Key contributions to this literature include Aghion and Howitt (1992), (1998), Grossman and Helpman (1991), and Romer (1990).

[2] Examples include Griliches (1980), Griliches and Lichtenberg (1984a), Mansfield (1980), Cameron (1996), Cameron, Proudman, and Redding (1998), Griffith, Redding, and Van Reenen (2000), and many others. See Mohnen (1996) for a survey of this literature.

[3] See Griliches (1992) for a survey of the inter-industry spillovers literature. Studies of international spillovers include Coe and Helpman (1995), Eaton and Kortum (1999), Franzen (2000), Jaffe and Trajtenberg (1998), and Keller (1997).

evidence in support in this idea is provided by Jaffe (1986), Eaton *et al.* (1998), and Griffith *et al.* (2000). In a regression of patents and profits on R&D activity, Jaffe (1986) 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 distance in technology space). That is, other firms' R&D activity has a greater effect on the patenting and profits of firms that themselves undertake more R&D. Using industry-level data for a panel of OECD countries, Griffith *et al.* (2000) find evidence that R&D raises the rate at which technology is transferred from frontier to non-frontier countries. This result is robust across a wide range of different econometric specifications and to the inclusion of a whole series of control variables.

A third literature has examined productivity convergence at the country and industry-level. A number of studies find large cross-country differences in productivity.[4] However, controlling for the determinants of long-run productivity levels, there is evidence of aggregate productivity convergence ('conditional convergence').[5] Several papers find evidence that aggregate productivity convergence is contingent on the promotion of absorptive capacity; for example, Benhabib and Spiegel (1994) find an important role for human capital, while Abramovitz (1986) emphasizes 'social capability'. There is also a large body of evidence of productivity convergence at the industry level.[6] Many studies find that the size of cross-country productivity differences varies across industries, casting doubt on the assumption of neutral technology differences often maintained by international trade economists.[7]

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[4]These include Acemoglu and Zillibotti (2001), Hall and Jones (1999), Harrigan (1999) and Prescott (1998).

[5]See, for example, Dowrick and Nyugen (1989), Dowrick (1992), Benhabib and Spiegel (1994), Bernard and Jones (1996a), (1996b), and Hansson and Henrekson (1994a).

[6]Examples include Bernard and Jones (1996a), (1996b), Cameron (1996), Cameron, Proudman, and Redding (1998), Dollar and Wolff (1988), (1994), Dowrick (1989), Griffith *et al.* (2000), Hansson and Henrekson (1994b), and Jorgenson and Kuroda (1990).

[7]See, for example, van Ark and Pilat (1993), Cameron (1996), Cameron, Proudman, and Redding (1998), Harrigan (1997), (1999), and Jorgenson and Kuroda (1990).

The theoretical model presented in this paper reconciles empirical evidence of R&D-based innovation, R&D's role in promoting absorptive capacity, and productivity convergence.[8] Countries converge to their own steady-state equilibrium levels of relative productivity, so that long-run differences in productivity levels across both countries and industries may exist. These emerge as equilibrium outcomes of the model, and depend on both incentives to undertake R&D and the productivity of these R&D investments.

The paper is structured as follows. Section 2 extends the Aghion and Howitt (1992), (1998) quality ladder model of growth to incorporate technology transfer and R&D-based absorptive capacity. A reduced-form equation for TFP growth is derived of exactly the same form as estimated in the empirical literatures on R&D, productivity growth, and productivity convergence. In order to keep the analysis tractable, we present an overlapping generations version of the model and restrict attention to a single final goods sector. An Appendix available from the authors on request extends the analysis to allow for multiple final goods sectors. Section 3 reviews the empirical evidence on R&D, productivity growth, and convergence in the light of the predictions of the theoretical model. Section 4 concludes.

II R&D and Innovation

Introduction

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

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[8]In an important contribution, Klette and Griliches (2000) also attempt to reconcile the stylised facts of the micro-econometric work on R&D and productivity within a formal quality ladder framework. Whereas they focus on incorporating stochastic firm growth effects into their model, we focus on international technology transfer and absorptive capactiy.

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.[9]

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.[10] Technological change is modelled as a sequence of endogenous improvements in the quality or productivity of intermediate inputs.

The timing of agents' decisions 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 therefore irreversible. Those who enter the intermediate sector, spend period 1 acquiring the general human capital needed to produce intermediate inputs.[11] 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. Therefore, if research is unsuccessful, production of intermediate inputs occurs under

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[9]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.

[10]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.

[11]See Redding (2002) for an analysis of the case where human capital is specific to vintages of technology.

conditions of perfect competition.[12]

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,

$$U_{it} = c_{i2t} \tag{1}$$

Production

Following Aghion and Howitt (1992), 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,

$$y_{i2t} = A_{i2t}.x_{i2t}^{\alpha} k_{i2t}^{1-\alpha}, \qquad 0 < \alpha < 1 \tag{2}$$

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 inputs themselves are produced with labour according to a constant returns to scale technology,

$$x_{i2t} = h_{i2t}, \tag{3}$$

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[12]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 intermediate input producers takes place both when fundamental research is successful and when it is unsuccessful. This substantially complicates the analysis, without adding any insight.

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

Innovation and Technology Transfer

For economies that lie behind the technological frontier, productivity growth may occur as a result of both innovation and technology transfer. R&D activity will play an important role in determining the pace of each. However, it is plausible that some technology transfer may also occur independently of investments in R&D ('autonomous' technology transfer). Therefore, irrespective of whether research is successful or unsuccessful in period 1, we allow the quality or productivity of intermediate inputs to rise by a proportion $Q_i(A_{F1t}/A_{i1t}) \geq 1$ above the level inherited from the previous generation in period 1. If research is unsuccessful, autonomous technology transfer is the only source of productivity growth, and the period 2 productivity of intermediate inputs is given by,

$$\underline{A_{i2t}} = Q_i\left(\frac{A_{F1t}}{A_{i1t}}\right).A_{i1t} \tag{4}$$

where a bar underneath a variable indicates the state of the world where research is unsuccessful. F indicates the economy with the highest level of productivity (the technological frontier), and the function $Q_i(\cdot)$ is assumed to satisfy the following conditions, $Q_i(1) = 1$, $Q_i'(\cdot) > 0$, $Q_i''(\cdot) < 0$, $\forall\ i$. Intuitively, the further behind the technological frontier that a country lies, the greater the potential for productivity growth through technology transfer $(Q_i'(\cdot) > 0)$. However, although productivity growth rises as one moves further and further behind the technological frontier, it does so at a diminishing rate $(Q_i''(\cdot) < 0)$. One simple functional form satisfying these properties is the constant elasticity specification,[13]

$$Q_i\left(\frac{A_{F1t}}{A_{i1t}}\right) = \left(\frac{A_{F1t}}{A_{i1t}}\right)^{\mu_i}, \qquad 0 < \mu_i < 1, \qquad \forall\ i \tag{5}$$

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[13] Although the above properties are extremely plausible, it is straightforward to consider the case when they are not satisfied.

Although we term such technology transfer autonomous because it proceeds independently of R&D activity, its pace is likely to vary across countries as a function of institutions, government policy, levels of general human capital, openness to trade, and other variables. We capture this cross-country variation here with the parameter μ_i. In the empirical studies examined below, controls are included for these other considerations.

If research is successful, the quality or productivity of intermediate inputs is raised by a proportion $\Gamma_i > 1$ over the level that would be achieved through technology transfer alone. 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 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).[14] Research is an inherently uncertain process, and the parameter λ_i captures productivity in research which may again vary across countries.

We follow Aghion and Howitt (1998) and Howitt (2000) in allowing the size of innovations Γ_i to be a function of a country's distance behind the technological frontier. Rather than assuming that non-frontier countries jump straight to the frontier when innovations occur, we allow this functional relationship to be continuous, $\Gamma_i = \Gamma_i\left(\frac{A_{F1t}}{A_{i1t}}\right)$, $\Gamma_i(1) > 1$, $\Gamma_i'(\cdot) > 0$, $\Gamma_i''(\cdot) < 0$, $\forall\, i$. Although being behind the technological frontier increases the size of innovations ($\Gamma_i'(\cdot) > 0$), the magnitude of the increase in the size of innovations diminishes as one moves further and further

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[14] 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 H_{it}^R 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.

behind the frontier ($\Gamma_i''(\cdot) < 0$). With a constant elasticity functional form,

$$\Gamma_i\left(\frac{A_{F1t}}{A_{i1t}}\right) = \gamma.\left(\frac{A_{F1t}}{A_{i1t}}\right)^{\phi_i}, \qquad \gamma > 1, \quad 0 < \phi_i < 1, \quad \forall\, i \tag{6}$$

In the frontier country with the highest TFP level ($A_{i1t} = A_{F1t}$), the size of innovations is $\gamma > 1$, exactly as in the conventional quality ladder model of Aghion and Howitt (1992). In non-frontier countries ($A_{i1t} < A_{F1t}$), R&D activity also facilitates the assimilation of ideas from the frontier, and the size of innovations is therefore increased. The parameter ϕ_i determines the speed with which the size of innovations varies with the technological gap, and is again allowed to vary with for example government policy and institutions. Combining research activity and autonomous technology transfer, the period 2 quality or productivity of intermediate inputs if research is successful is given by,

$$\overline{A}_{i2t} = \gamma.\left(\frac{A_{F1t}}{A_{i1t}}\right)^{\phi_i + \mu_i} A_{i1t} \tag{7}$$

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

General Equilibrium

Equilibrium Production in Period 2

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

$$\underline{\hat{w}_{i2t}} = \underline{\hat{q}_{i2t}} = \alpha \underline{A_{i2t}}\left(\underline{\hat{h}_{i2t}}\right)^{\alpha-1}(K_i)^{1-\alpha} \tag{8}$$

Equilibrium period 2 demand for labour in the intermediate sector equals supply, as endogenously determined by period 1 choices: $\underline{\hat{h}_{i2t}} = \hat{H}_{it}^P$.

If research is successful, the successful researcher receives a patent for the new technology, and is the monopoly supplier of intermediate inputs produced using that technology. This technology is $\Gamma_i > 1$ times more productive than the next best

technology, $\overline{A_{i2t}} = \Gamma_i.\underline{A_{i2t}}$. 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 next best technology, and the constraint that final goods production using intermediate inputs produced with the new technology is no more expensive than production using the next best technology,

$$\max_{x_{i2t},w_{i2t}} \{q_{i2t}.x_{i2t} - w_{i2t}h_{i2t}\} \tag{9}$$

subject to:
$$x_{i2t} \geq 0$$
$$x_{i2t} = h_{i2t}$$
$$w_{i2t} \geq \underline{w_{i2t}}$$
$$b_{i2t}\left[\overline{A_{i2t}}, q_{i2t}, r_{i2t}\right] \leq b_{i2t}\left[\underline{A_{i2t}}, \underline{q_{i2t}}, r_{i2t}\right]$$
$$q_{i2t} = \alpha A_{i2t} x_{i2t}^{\alpha-1} k_{i2t}^{1-\alpha}$$

where $b_{i2t}(\cdot)$ is the unit cost for final goods production, as a function of the productivity of intermediate inputs (A_{i2t}), their price (q_{i2t}), and the rental rate for capital (r_{i2t}). The next best technology is freely available to all intermediate producers, and therefore the wage received with this technology $(\underline{w_{i2t}})$ equals intermediate input producers' VMP (equation (8)).

In equilibrium, the holder of the patent to the new technology will pay intermediate input producers a wage no higher than their outside option, and hence,

$$\overline{\hat{w}_{i2t}} = \underline{\hat{w}_{i2t}} = \underline{\hat{q}_{i2t}} = \alpha \underline{A_{i2t}} \left(\overline{\hat{h}_{i2t}}\right)^{\alpha-1} (K_i)^{1-\alpha} \tag{10}$$

For simplicity, we consider the case of 'drastic' innovations where it is cheaper for final goods producers to employ the new rather than the next best technology at the profit-maximizing monopoly price.[15] The profit-maximizing monopoly price is the standard mark-up over marginal cost,

$$\overline{\hat{q}_{i2t}} = \frac{1}{\alpha}.\overline{\hat{w}_{i2t}} = \frac{1}{\alpha}.\underline{\hat{w}_{i2t}} \tag{11}$$

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[15]The condition for an innovation to be drastic is $\Gamma_i > \alpha^{-\alpha}$, 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.

and equilibrium profits from intermediate input production are,

$$\overline{\hat{\pi}}_{i2t} = \left(\frac{1-\alpha}{\alpha}\right) . \hat{w}_{i2t}\overline{\underline{\hat{h}}}_{i2t} \tag{12}$$

Equilibrium period 2 demand for labour in the intermediate sector must again equal supply as endogenously determined by period 1 choices: $\overline{\hat{h}}_{i2t} = \hat{H}_{it}^P$.

Equilibrium Period 1 Choice Between Research and 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 $(\hat{V}_{it}^P)$.

With probability λ_i, an individual researcher obtains the patent to the new technology and enjoys an equilibrium flow of profits equal to (12). With probability $(1-\lambda_i)$, she fails to obtain the patent and receives zero period 2 returns from research.[16] The expected lifetime return from research is thus $\hat{V}_{it}^R = \lambda_i \left(\frac{1-\alpha}{\alpha}\right) \underline{\hat{w}_{i2t}} \hat{H}_{it}^P$.

From the analysis above, 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 the next best technology. The expected lifetime return from intermediate input production is thus $\hat{V}_{it}^P = \underline{\hat{w}_{i2t}}$.

In equilibrium, the number of intermediate input producers equals the supply of workers minus those who choose to enter the research sector: $\hat{H}_{it}^P = H_i - \hat{H}_{it}^R$. Combining these relationships, the requirement that the expected lifetime return from research equals the expected lifetime return from intermediate production is given by,

$$1 = \lambda_i \left(\frac{1-\alpha}{\alpha}\right) (H_i - \hat{H}_i^R) \tag{13}$$

For parameter values such that $\lambda_i \left(\frac{1-\alpha}{\alpha}\right) H_i > 1$, we have an interior equilibrium and equation (13) defines a unique equilibrium level of research employment $(0 < \hat{H}_i^R <$

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

H_i).

Productivity Growth and Convergence

From the final goods production technology (2), the expected rate of TFP growth between two generations is simply,

$$\mathsf{E}_{t-1} \ln \left(\frac{A_{i1t}}{A_{i1t-1}} \right) = \underbrace{\lambda_i \hat{H}_{it-1}^R \ln \gamma}_{\text{term 1}} + \underbrace{\mu_i \ln \left(\frac{A_{F1t-1}}{A_{i1t-1}} \right)}_{\text{term 2}} + \underbrace{\lambda_i \hat{H}_{it-1}^R \phi_i \ln \left(\frac{A_{F1t-1}}{A_{i1t-1}} \right)}_{\text{term 3}} \quad (14)$$

where E is the expectations operator. This equation for expected growth has the standard properties that we would expect from a Schumpeterian model of endogenous growth. R&D-based innovation is a central determinant of the economy's growth rate (Term 1), and the expected rate of growth is increasing in the size of innovations (γ), the probability of research success (λ_i), and equilibrium research employment ($\hat{H}_i^R$).

In addition, the model is consistent with empirical findings of productivity convergence (Terms 2 and 3). The potential for technology transfer implies that, *other things equal*, countries further behind the technological frontier ($A_{i1t-1} < A_{F1t-1}$) will have faster rates of productivity growth. Although all countries behind the technological frontier have the *potential* to achieve productivity growth through technology transfer, note that the realization of this potential is dependent upon institutions and government policy which affect the pace of autonomous technology transfer (as reflected in the parameter μ_i in Term 2) as well as upon R&D-based absorptive capacity (as captured by Term 3). By engaging in R&D, countries increase their ability to assimilate and understand the discoveries of others, thereby raising the speed at which technology transfer occurs.

Equation (14) implies a long-run cointegrating relationship between TFP in the frontier and TFP in non-frontier countries. Combining equation (14) for a non-frontier country i and for the frontier country F, we obtain a first-order difference equation

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for the evolution of relative TFP,

$$\mathsf{E}_{t-1}\triangle \ln \tilde{A}_{i1t} = \left(\lambda_F \hat{H}^R_{Ft-1} - \lambda_i \hat{H}^R_{it-1}\right) \ln \gamma - \left(\lambda_i \hat{H}^R_{it-1}\phi_i + \mu_i\right) \ln \tilde{A}_{i1t-1} \qquad (15)$$

where $\tilde{A}_{i1t} = A_{F1t}/A_{i1t}$. In steady-state equilibrium, the frontier will be whichever country has the highest expected rate of growth through innovation alone (Term 1 in equation (14)), and the model allows for endogenous switches in technological leadership.[17] A steady-state equilibrium level of relative TFP will exist for all other countries i, such that the expected rate of 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 both innovation and technology transfer exactly equals expected TFP growth in the frontier from innovation alone. From equation (15), the steady-state or long-run cointegrating level of relative TFP in a non-frontier country i is,

$$\ln \tilde{A}^*_{i1} = \frac{\left(\lambda_F \hat{H}^R_F - \lambda_i \hat{H}^R_i\right) \ln \gamma}{\left(\lambda_i \hat{H}^R_i \phi_i + \mu_i\right)} \qquad (16)$$

Steady-state equilibrium relative TFP depends on institutions and government policy which affect the productivity of research (λ_i, λ_F); equilibrium research employment ($\hat{H}^R_i$, $\hat{H}^R_F$); the size of innovations in the frontier (γ); and political and economic variables which shape the speed of autonomous and absorptive capacity-based technology transfer (μ_i and ϕ_i). Other things equal, countries that undertake less R&D must lie further behind the technological frontier in steady-state in order for their expected rate of growth through innovation and technology transfer to equal the expected rate of growth through innovation alone in the frontier.

The analysis so far has been undertaken at the country-level. However, it is straightforward to extend the model to introduce multiple final goods sectors, in which case a directly analogous relationship to equation (14) holds at the industry-level.[18]

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[17]For a discussion of leapfrogging in technological leadership in a historical context, see Brezis *et al.* (1993).

[18]An Appendix available from the authors on request undertakes this extension.

Industry TFP growth depends on R&D-based innovation (Term 1), autonomous technology transfer (Term 2), and R&D-based absorptive capacity (Term 3). Productivity convergence occurs within industries, and in each industry a steady-state equilibrium level of relative TFP exists. The country that is the technological frontier in one sector may well lie behind the frontier in others, and changes in technological leadership may occur in individual sectors.

III   Empirical Evidence

Equation (14) takes exactly the same form as the reduced-form regressions estimated in the empirical literature on R&D, productivity growth, and productivity convergence. The micro-econometric literature on R&D and productivity growth focuses almost exclusively on the first of the three terms on the right-hand side. Industry or firm-level TFP growth is regressed on R&D activity. The preferred measure is typically the ratio of R&D to output, although a variety of an alternative measures are employed,[19]

$$\triangle \ln A_{ijt} = \rho \left(\frac{R}{Y} \right)_{ijt-1} + \beta X_{ijt-1} + u_{ijt-1} \tag{17}$$

where ρ is interpreted as the social rate of return to R&D, and X is a vector of control variables. The exact estimate of ρ varies across studies according to sample (time, country, and industry), the exact definition of R&D used (privately funded, publicly funded, or total), and whether spillovers of R&D knowledge across industries are allowed. For example, Griliches and Lichtenberg (1984b) find estimated coefficients of between 0.21 and 0.76, while Schankerman (1981) and Scherer (1982), (1984) obtain estimates of 0.24-0.73 and 0.29-0.43 respectively. Nonetheless, a positive and statistically significant value of ρ is a robust empirical finding of this literature.

Most studies use data from the United States, which is typically at or close to

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[19]The theoretical model suggests the use of R&D employment data. These are not as widely available across countries at the disaggregated industry level as information on R&D expenditure. We discuss below results using both the ratio of R&D to output and R&D unnormalized by output.

the technological frontier. There is therefore likely to be little potential for technology transfer, and the estimated coefficient on R&D will largely capture productivity growth due to innovation. However, the theoretical model of the previous section implies that these studies will typically underestimate the social rate of return to R&D in non-frontier countries. From the above, the coefficient on R&D in the frontier is $\rho_{Fj} \equiv \lambda_{Fj} \ln \gamma_j$ and solely reflects innovation. However in non-frontier countries, the coefficient is given by $\rho_{ij} \equiv \lambda_{ij} \left[\ln \gamma_j + \phi_{ij} \ln(A_{F1jt-1}/A_{i1jt-1}) \right]$, and includes the impact of R&D on productivity growth through absorptive capacity. Below, we review empirical evidence suggesting that these effects are both statistically and quantitatively important.

The empirical literature on productivity convergence is largely concerned with the second of the three terms on the right-hand side of equation (14), and considers models of the following form,

$$\triangle \ln A_{ijt} = \mu \ln \left(\frac{A_F}{A_i} \right)_{jt-1} + \beta X_{ijt-1} + e_{ijt-1} \tag{18}$$

where μ corresponds to the rate of productivity convergence, and X is again a vector of control variables.[20]

Cameron (1996), Cameron, Proudman, and Redding (1998), and Griffith *et al.* (2000) provide direct estimates of equation (18). For a panel of UK manufacturing industries, Cameron, Proudman, and Redding (1998) find an estimated coefficient on distance from the technological frontier (defined as industry TFP relative to the United States) of around 0.10 (standard error 0.04). Using data on 14 manufacturing industries from 12 OECD countries, and defining distance from the technological frontier as industry TFP relative to the country with the highest TFP level, Griffith

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[20]Country-level findings of convergence in labour productivity or income per capita include, among others, Benhabib and Spiegel (1994), Dowrick and Nyugen (1989), Dowrick (1992), and Hansson and Henrekson (1994a). Bernard and Jones (1996a), (1996b) examine the implications of equation (18) for the evolution of relative productivity levels at the industry-level across 14 OECD countries. Other industry-level findings of convergence include Dollar and Wolff (1988), (1994), Dowrick (1989), Hanson and Henrekson (1994b), and Jorgenson and Kuroda (1990).

et al. (2000) estimate a coefficient of approximately 0.09 (standard error 0.01). For a panel of Japanese manufacturing industries and using a measure of industry TFP relative to the United States, Cameron (1996) finds an estimated coefficient of around 0.06 (standard error 0.02). The smaller estimated effect for Japan may be well be explained by the fact that in a number of industries Japanese TFP overtook US TFP levels in the 1980s.

While each of these empirical literatures focuses on one of the three terms on the right-hand side of equation (14), the theoretical model above suggests that all three terms are important determinants of productivity growth. A clear and potentially empirically falsifiable prediction of the theory is that there should be a positive estimated coefficient on an interaction term between R&D and distance from the technological frontier. Griffith *et al.* (2000) estimate an econometric equation including all three sets of considerations,

$$
\triangle \ln A_{ijt} = \underbrace{\rho \left(\frac{R}{Y} \right)_{ijt-1}}_{\text{Term 1}} + \underbrace{\mu \ln \left(\frac{A_F}{A_i} \right)_{jt-1}}_{\text{Term 2}}
$$
$$
+ \underbrace{\phi \left(\frac{R_i}{Y_i} \right)_{jt-1} \ln \left(\frac{A_F}{A_i} \right)_{jt-1}}_{\text{Term 3}} + \beta X_{ijt-1} + \omega_{ijt}
$$

(19)

where X is again a vector of control variables. The TFP measures used are superlative index numbers that control for variation in hours worked and the skill composition of employment. Estimation includes a full set of country-industry fixed effects to controls for unobserved heterogeneity ("within groups") and a full set of time dummies to control for world macroeconomic shocks.

Table 1 summarizes results from Griffith *et al.* (2000). Column (1) begins by including the ratio of R&D to output (Term 1, capturing R&D-based innovation) and distance from the technological frontier (Term 2, capturing autonomous technology transfer). Both coefficients are signed according to economic priors and are highly

statistically significant.[21] The implied social rate of return to R&D-based innovation ρ is over 60% which is high relative to many existing US studies. This is consistent with the theoretical model presented above. The United States is the technological leader in the majority of the industries considered, whereas the estimation sample here includes non-frontier countries. The higher estimated social rate of return on the R&D innovation variable (Term 1) may therefore reflect the fact that in non-frontier countries R&D also has the potential to generate productivity growth through technology transfer. That is, the theoretical model implies an omitted variable for R&D-based absorptive capacity (Term 3).

In Column (2), we test this prediction of the theory by explicitly including a separate term for R&D-based absorptive capacity. The estimated coefficient on this variable is positive and statistically significant at the 5% level, providing empirical support for R&D's role in facilitating the transfer of technology.[22] Having controlled for R&D-based absorptive capacity, the implied social rate of return on the linear R&D innovation variable ρ falls to around 40% which is more in line with existing US studies.

Column (3) 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 instruments are highly statistically significant in the first-stage regressions. Conditional on the covariates, we find no evidence of serial correlation in the residuals, as is required for the lagged values to be valid instruments. 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.

Columns (4) and (5) summarize the results of a robustness test including addi-

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[21]Estimating the model with R&D un-normalized by output yields a similar pattern of results. The estimated coefficient on the level of R&D is 0.017 (standard error 0.007) and that on distance from the technological frontier is 0.111 (standard error 0.014).

[22]Estimating the model with R&D un-normalized by output again yields a similar pattern of results. For example, the estimated coefficient on the R&D interaction is 0.194 (standard error 0.056).

tional control variables. As discussed above, the pace of what we term autonomous technology transfer may vary across countries with government policy, institutions, and variables such as human capital. The country-industry fixed effect will control for permanent differences across countries and industries in the speed of technology transfer due to institutions and government policy. The specifications in Columns (4) and (5) also allow the rate of technology transfer to vary with countries' levels of human capital. Both the level of human capital and the level of human capital interacted with relative TFP are included as control variables. As is clear from the table, the R&D results (Terms 1 and 3) are robust to the inclusion of these additional variables. The estimated coefficient on linear relative TFP falls and is no longer statistically significant, implying that the transfer of technology across countries is largely explained by investments in R&D, levels of human capital, and permanent features of countries and industries captured in the fixed effect. These results are confirmed in Column (5), where we treat relative TFP at $t-1$ as endogenous and instrument with lagged values of the explanatory variables. The instruments are again highly statistically significant in the first-stage regressions, and the results of the Sargan and serial correlation tests provide support for the IV estimates.

This empirical finding of R&D-based absorptive capacity is robust across a wide range of econometric specifications, to the inclusion of further control variables, and to the use of a number of alternative TFP measures. Independent empirical support is provided by the firm-level estimates of Jaffe (1986) and the country-level analysis of a computable general equilibrium model in Eaton *et al.* (1998).

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

ΔTFP_{ijt}		(1)	(2)	(3)	(4)	(5)
Estimation		Within Groups	Within Groups	IV	Within Groups	IV
R/Y_{ijt-1}	ρ	0.623	0.433	0.382	0.427	0.383
		(0.168)	(0.179)	(0.189)	(0.188)	(0.183)
$RTFP_{ijt-1}$	μ	0.097	0.068	0.072	0.024	0.034
		(0.014)	(0.016)	(0.020)	(0.021)	(0.025)
$(RTFP * R/Y)_{ijt-1}$	ϕ	-	1.00	1.345	0.815	1.14
			(0.344)	(0.398)	(0.348)	(0.404)
Year dummies		yes	yes	yes	yes	yes
Fixed effects		yes	yes	yes	yes	yes
Control variables		basic	basic	basic	extended	extended
Serial Correlation		0.373	0.185	0.969	0.318	1.060
Sargan (p-value)		-	-	0.072	-	0.086

Notes: this table summarizes empirical results from Griffith et al. (2000); sample contains 1801 observations from 1974-1990; numbers below coefficients in parentheses are robust standard errors; all regressions include country-industry effects (i.e. within groups estimation); observations are weighted using industry shares of total manufacturing employment in 1970; $RTFP_i$ is relative level of TFP defined as ln(TFP in frontier) minus ln(TFP in country i); R/Y is R&D divided by value added; 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; the "basic" control variables included in columns (1) - (3) are contemporaneous TFP growth in the frontier and a full set of time dummies; the "extended" control variables included in columns (4) and (5) are basic controls plus the lagged level of human capital (H_{ijt-1},measured by percentage of the population which has attained tertiary education) and the lagged level of human capital interacted with RTFP; 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) $H_{ijt-1}, (RTFP_{ijt-2} * H_{ijt-1}), (RTFP_{ijt-3} * H_{ijt-1})$.

IV   Conclusions

This paper has presented a single unified framework that integrates the theoretical literature on Schumpeterian endogenous growth and the empirical literatures on R&D, productivity growth, and productivity convergence. Starting from a structural model of endogenous innovation and growth following Aghion and Howitt (1992), (1998), we provide microeconomic foundations for the reduced-form equations for Total Factor Productivity (TFP) growth estimated using industry-level data.

The theoretical model identifies three key sources of productivity growth: R&D-

induced innovation, technology transfer, and R&D-based absorptive capacity. While the micro-econometric literature on R&D and productivity concentrates on the first, the empirical literature on productivity convergence focuses on the second. We review empirical evidence that all three sets of considerations are statistically and economically important, and confirm a key empirical prediction of the theory that there should be a positive effect on productivity growth from an interaction term between R&D and distance from the technological frontier.

Long-run cross-country differences in productivity emerge endogenously within the model, and the analysis implies that many existing studies underestimate R&D's social rate of return in so far as they neglect absorptive capacity.

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