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Market Size or Acceleration Effects; Comparing Hypotheses to Explain Skill Biased Technical Change

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Market Size or Acceleration Effects;

Comparing Hypotheses to Explain Skill Biased Technical Change*

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Abstract:
Skill-biased technical change has occupied empirical economists for much of the 90s. However, the empirical literature has not progressed much beyond observing a positive correlation between technology indicators and demand shifts. Two hypotheses on the root causes of skill biases in technical change, the acceleration effect and the market size effect, have been suggested in the literature. In this paper both are studied in a unified theoretical framework to derive the sufficient and necessary conditions for both hypotheses. Confronting them with the evidence the paper concludes that it favours the acceleration hypothesis but further empirical work needs to be done.

Keywords: Skill-Bias, Endogenous Growth, Product-Lifecycle
JEL-Classification: J23; J24; J31; O15; O31; O33

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Introduction

Compared to high skilled workers, the labour market position of low skilled workers has deteriorated dramatically over the 80s and early 90s. The most well known manifestation of that deterioration is the rise in relative wages that low-skilled American workers endured.[1] Card and DiNardo (2002) show that after falling in the late 70s the relative wage of college to high school educated workers rose by over 20% from 1.3 to 1.6 between 1980 and 2000. Meanwhile the supply of college educated labour increased steadily from 0.4 to about 0.7 per unskilled worker over the same period. From this evidence, the simultaneous increase in relative supply, employment *and* wages, it can be concluded that the relative demand for high skilled workers has outgrown relative supply during the 80s.

Similar trends in demand have been observed throughout the OECD and beyond.[2] Berman and Machin (2000) survey the abundant empirical evidence and conclude that a consensus is forming on the underlying causes of these developments. Because many authors have found robust positive correlations between the use of new technologies and the skill intensity of production, the shift in relative labour demand is attributed to the widespread introduction of new technologies that require or favour the employment of skilled labour. This is known as the Skill-Biased Technical Change (SBTC) hypothesis.[3]

But for all their empirical rigour and econometric sophistication, this literature does little more than attribute to technological change what we cannot attribute to something else. The observed correlations between skill intensity and the use of new technology strongly suggest a link but do not help us understand its nature. Autor, Levy and Murnane (2003) recognise this lacunae and seek to further our understanding by differentiating between routine and non-routine tasks within jobs. They find that computers are substitutes for routine labour tasks and increased computer use therefore shifts demand towards more skilled labour even within occupations. Although the data suggest that that bias is strong in computers, the question remains how it got there. Understanding the nature of technical change also requires an answer to why new technology was biased towards skilled labour during the 80s. And that understanding is crucial if science and technology policy is to be well informed.

In the literature, two hypotheses have emerged to address this issue. The first, developed by Kiley (1999) and Acemoglu (1998, 2000, 2002), views skill bias as a characteristic of new technologies by design and explains why profit maximising R&D labs may choose to develop skilled labour using innovations in spite of rising relative wages. Acemoglu (2002) for example shows that in a model with endogenous innovation, technical change can be biased towards skilled labour in response to a positive supply shock. In his model a positive supply shock makes the development and introduction of skilled labour using technologies more worthwhile because the fixed costs of developing such technologies can be spread over a larger number of potential users, increasing the returns to developing such technologies. He labels this the ‘market size effect’ because

[1] See for example Murphy and Welch (1992, 1993), Bound and Johnson (1992), Katz and Murphy (1992), Juhn, Murphy and Pierce (1993), Gottschalk and Moffitt (1994), Autor, Katz and Krueger (1998), Katz and Autor (1999) and Goldin and Katz (2000).

[2] Although the resulting wage divergence seems to be typical only for Anglo-Saxon countries (US, UK, New Zealand and Canada). See for example Freeman and Katz (1994), Katz and Revenga (1989), Katz, Loveman and Blanchflower (1995), Davis (1992), Machin (1996) and Nickell and Bell (1995).

[3] This “consensus”, however, is not uncontested. Many (see Feenstra and Hanson (1996) and Feenstra (2000)) have proposed that international trade has a role to play and Krugman (2000) showed that even information asymmetries and sorting in the labour market are a potential explanation for the observed labour market trends. The alternatives to the SBTC-hypothesis, however, lie beyond the scope of this paper, in which I concentrate on hypotheses that explain SBTC itself.

the size of the market for skilled labour using technologies increases with their supply. According to this hypothesis R&D workers designed the computer to be complementary to skilled workers and the complex non-routine tasks they perform, whereas they were also designed to substitute for the low skilled workers and their routine tasks.

In Acemoglu (2002) it is shown that the market size effect may overcome the natural tendency for relative wages to fall when high and low skilled labour are gross-substitutes. The empirical evidence does not contradict this hypothesis and its predictions are in line with observed wage and employment patterns. Furthermore the model predicts that, because new technology is *designed* to be skill biased, the deterioration in the position of low skilled labour is a permanent and steady state result.

The alternative acceleration hypothesis is founded in two empirical facts the market size effect does not require or explain.[4] First it basically argues that any technological change gives the skilled, educated or more able workers a comparative advantage in the labour market. The comparative advantage of the educated follows from their assumed higher ability to adapt or accumulate the required human capital to operate the new technologies and produce the new goods. Basically one could argue the introduction of new technologies causes all tasks to become non-routine as they are now new. Under this hypothesis a new technology is not designed to complement high skilled labour but works out that way merely because it is new. As the novelty wears off, routine elements of the new activity will be identified and the initial skill bias will be reduced, disappear or may even turn towards low skilled labour. The empirical evidence in support of that assumption is solid.[5] Skill bias is therefore linked to the speed at which new innovations enter the economy, not to the type of labour they were designed to complement.

The second empirical fact is an increase in the rate at which new goods, services or intermediates enter the economy, which will then cause an increase in the demand for skilled labour.[6] To explain the acceleration in technical change most authors rely on the exogenous discovery of a new general-purpose technology (GPT) such as computers or ICT.[7] Such a GPT, upon introduction, allows for the rapid expansion of the number of new goods, services and intermediates produced. The acceleration hypothesis, however, also predicts that once the rate of technical change returns to normal so do relative wages.

This provides a first testable prediction that distinguishes the two proposed hypotheses. The most recent evidence on relative wage developments does suggest a slowdown and perhaps reversal in relative demand trends, but as both demand, supply and institutional factors interact on the labour market, it is hard to identify the demand trends.[8] In addition the problem is that we cannot determine empirically when the economy reaches a steady state. The acceleration of technical change following the introduction of a new GPT might well span several years or even decades, whereas the effects of exogenous supply shocks could easily be absorbed much faster. This implies that long periods of higher relative wages are compatible with both hypotheses.

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[4] Examples of the acceleration hypothesis in theoretical models include Galor and Tsiddon (1997), Greenwood and Yorukoglu (1997), Caselli (1999), Rubinstein and Tsiddon (1999), Galor and Moav (2000), Aghion (2001) and Aghion, Howitt and Violante (2002). Most have credited Nelson and Phelps (1966) for first presenting a model that links the rate of technical change to the demand for skilled labour.

[5] See for example Schultz (1975), Bartel and Lichtenberg (1987), Audretsch (1987) and Xiang (2002)

[6] Empirical evidence presented by for example Kortum and Lerner (1997) and Greenwood and Uysal (2004) suggests such an acceleration might indeed have occurred during the 80s.

[7] Greenwood and Yorukoglu (1997) also present evidence supporting the acceleration hypotheses from periods that refer to the introduction of earlier GPTs such as steam and electricity.

[8] Acemoglu suggested Card, Dinardo and Autor, Katz and Keirney. The papers are yet to be found. Ask Daron.

To come up with predictions that do allow empirical research to distinguish between the two, a further analysis of the underlying micro foundations would be helpful. The acceleration models in the literature, however, typically lack such micro foundations. In most acceleration models the crucial transmission from an exogenous GPT-introduction to the endogenous labour market responses remains inside a black box. In this paper I will therefore present and analyse a model in which a GPT-induced acceleration in innovation is taken out of the black box and provide the acceleration hypothesis with the same sophisticated micro foundations Acemoglu (2002) provides for the market size effect.

To capture the full dynamics of the acceleration hypothesis one must explicitly model the generation of new technologies as well as the process that ages them. Fortunately the idea of aging technologies and changing factor requirements over time is not entirely new to the literature. Krugman (1979) already presented a model in which he assumed that new products and technologies require high skilled labour to produce them in the initial stages of their existence.[9] In that model knowledge about a new product accumulates and diffuses and eventually less educated workers - Krugman positioned them in the South - can effectively compete and take over production. He took his idea from Vernon (1966), who labelled it the Product Life Cycle (PLC). Grossman and Helpman (1991a) presented a model that introduces an endogenous innovation driven PLC in the basic Krugman (1979) framework using by now standard modelling techniques in growth theory.[10]

Although the PLC-literature primarily aimed at explaining international patterns of trade, the idea of a PLC can also be applied in a closed economy context to formalise the ‘aging’ idea and make the transmission of a GPT to relative labour demand explicit.[11] If we assume that products can be produced by high skilled labour only in the first stage and further (process) R&D is required to enable low skilled workers to produce them in the second, we have a simple two-stage PLC where the “birth”- and “transition”-rates can easily be endogenised as in Grossman and Helpman (1991a). Because R&D resources now have two alternative uses, developing high skilled complementary ‘new’ products, or low skilled complementary processes for existing products, a comparison can easily be made to models that explicitly require the R&D sector to allocate its resources between skilled and unskilled labour using innovations.

The introduction of a new GPT in an endogenous PLC-model can be thought of as an asymmetric shock to the productivity of R&D workers in innovation. By increasing the productivity of R&D workers in the design of new products and services the R&D sector reallocates resources and increases the range of new goods quickly. This acceleration then generates skill bias in aggregate labour demand. As the new GPT is exhausted productivity in the R&D sector returns to normal levels and so will relative wages as cost reducing process innovations gradually increase the relative demand for low skilled labour back to normal. An additional testable prediction of the acceleration hypothesis is now that R&D resources are reallocated towards generating new products and services, whereas developing new processes or machines for existing producers should reduce the skill intensity of production. Also the acceleration hypothesis requires an asymmetric shift in R&D productivity parameters, whereas they can be assumed to remain stable for the market size effect. A closer look at the necessary and sufficient conditions to generate acceleration and market size effects in the context of a general innovation driven

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[9] As indeed did Nelson and Phelps (1966), Vernon (1966) and several others before him.

[10] Other references for extensions of the Krugman framework include Dollar (1986), Jensen and Thursby (1986, 1987) and Grossman and Helpman (1991a).

[11] Jovanovic (2004) is a recent example of using the skill demand dimensions of the life cycle to explain wage or income inequality. In his paper, however, the framework is applied to between country inequality.

endogenous growth model may shed further light on the relative importance of both hypotheses.

The paper shows that the identification of sufficient and necessary conditions for the two alternative hypotheses is possible when we study them in a unified framework. In providing such a framework the paper shows that these conditions are empirically testable and that the available evidence in the literature favours the acceleration hypothesis. A definite dismissal of the market size effect, however, is not warranted at this stage. As the source of bias needs to be understood in order to asses the need and possibilities for policy action, the paper concludes that further empirical research along the lines here suggested would be valuable.

The remainder of the paper is structured as follows. Section 1 presents a basic general two-sector innovation driven growth model that endogenises skill bias along the lines of Acemoglu (2002) and may or may not be characterised by a product life cycle as in Grossman and Helpman (1991a). Section 2 analyses the possible equilibria and identifies the restrictions required to generate a market size effect and specifications that generate the acceleration hypothesis. In this section these restrictions and conditions are confronted with the available empirical evidence in the literature. That will both give an indication of the relative plausibility and identify the empirical work that remains to be done. Section 3 concludes by discussing some empirical strategies that may distinguish the two hypotheses here presented.

Section 1: The Model

Consumers

The model presented below will follow standard variety expansion endogenous growth models closely.[12] First infinitely lived consumers save and consume in a standard fashion to maximise lifetime utility subject to a budget constraint. The problem is given by:

$$\max_{C(t)} : U = \int_0^\infty e^{-\rho t} \log C(t) dt \qquad \text{s.t.} \qquad Y(t) + rA(t) = C(t) + \dot{A}(t) \tag{1}$$

where ρ is the subjective discount rate and $C(t)$ is a consumption index to be defined below. Defining $E(t)$ to be the expenditure on consumption at time t and $P(t)$ the minimum price of one unit of the index, we obtain the standard Ramsey optimal savings rule:

$$\frac{\dot{C}(t)}{C(t)} \equiv \frac{\dot{E}(t)}{E(t)} - \frac{\dot{P}(t)}{P(t)} = r - \rho \tag{2}$$

Utility maximisation implies maximisation of the consumption index for any given level of expenditure in any period. A Dixit-Stiglitz love of variety consumption index is therefore maximised in every period subject to the intratemporal budget constraint:

$$\max_{c(i)} : C = \left(\int_0^n c(i)^\alpha di \right)^{1/\alpha} \qquad \text{s.t.} \qquad \int_0^n p(i)c(i)di \leq E \tag{3}$$

where $c(i)$ is the volume and $p(i)$ is the price of variety i consumed and time arguments have been dropped to save on notation. The first order conditions to this problem show that the intra-temporal consumption index is maximised by setting demand for an individual variety equal to:

$$c^D(i) = \left(\frac{p(i)}{P} \right)^{\frac{1}{\alpha-1}} \frac{E}{P} \tag{4}$$

where P is again the price index, earlier defined as the minimum price of a unit of the index:

$$P \equiv \frac{E}{C^*} = \left(\int_0^n p(i)^{\frac{\alpha}{\alpha-1}} di \right)^{\frac{\alpha-1}{\alpha}} \tag{5}$$

where C^* is the maximum value of the consumption index given expenditure E and prices $p(i)$. Consumers therefore save and consume according to an iso-elastic demand curve for all varieties allowing for variety expanding R&D investments as they can be financed up front out of savings and are worthwhile to undertake as new goods face a positive demand at any price.

[12] The structure is closest to that presented in Grossman and Helpman (1991b) chapter 4.

The Producers

Now we turn to the producers in the model. Assume monopolistic competition between firms that produce one variety each. Their profit maximisation problem is given by:

$$\max_{p(i)} : \pi(i) = y(i)p(i) - tc(i) \qquad \text{s.t.} \qquad y(i) = c^D(i) \tag{6}$$

where $y(i)$ is the volume and $tc(i)$ the total costs of production for variety i. It can easily be verified that to maximise profits producers must set prices equal to a fixed mark-up, $1/\alpha$, over marginal costs. Now assume there are two ranges of goods, n_H and n_L, that are produced with high and low skilled labour, respectively. Assume production functions are given by:

$$y_S{}^D(i) = b_S l_S(i)^\beta \qquad \forall i \in n_S \tag{7}$$

where S={H, L} indexes high and low skilled varieties. Facing the same demand function, competing for the same labour and restricted by the same production technology, within ranges firms will choose to employ the same quantity of labour and supply the same amount. That also implies that prices are set equal within ranges, as marginal costs are a function of the wage and employment levels. Setting production equal to consumption at profit maximising prices, inverting the production function and aggregating over the two goods ranges yields the aggregate labour demand functions:

$$L_S{}^D = \frac{\alpha\beta}{w_S} E_S \tag{8}$$

where E_S is the total expenditure on varieties in range n_S. Using $-S$ to signify "not-S" these expenditures can be written as:

$$E_S \equiv \left(1 + \left(\frac{n_{-S}}{n_S}\right)\left(\frac{w_{-S}}{w_S}\right)^{\frac{-\alpha\beta}{1-\alpha\beta}}\left(\frac{b_{-S}}{b_S}\right)^{\frac{\alpha}{1-\alpha\beta}}\right)^{-1} E \tag{9}$$

From Equation (8) one can then derive relative labour demand in function of relative wages. It is given by:

$$\frac{L_H}{L_L} = \frac{n_H}{n_L}\left(\frac{b_H}{b_L}\right)^{\frac{\alpha}{1-\alpha\beta}}\left(\frac{w_H}{w_L}\right)^{\frac{-1}{1-\alpha\beta}} \tag{10}$$

And profits per variety are given by:

$$\pi_S(i) = (1-\alpha\beta)E_S / n_S \qquad \forall i \in n_S \tag{11}$$

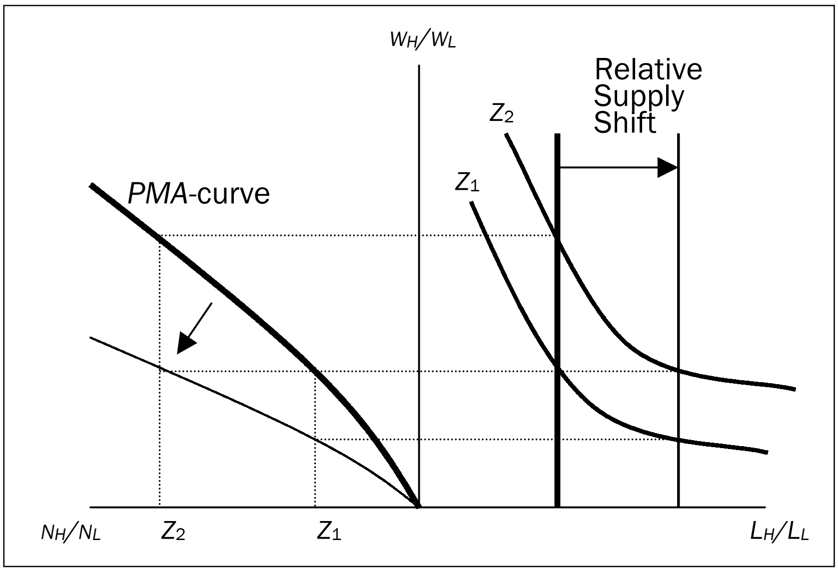
Note that stable market shares imply that profits per variety fall with the number of varieties in a given range. Cost minimisation yields iso-elastic aggregate demand curves for both types of labour in the model while imperfect competition allows producers to make positive profits and repay their up front R&D investments below.

Labour Market Equilibrium

For given relative employment levels Equation (10) can be rewritten to trace out a concave upward sloping curve in n_H/n_L-w_H/w_L-space. With inelastic exogenous labour supplies this curve represents the labour market equilibrium in the short run and therefore also in the steady state. Below it will be referred to as the Product Market Arbitrage or *PMA*-curve as it equates the relative marginal product of labour in production to the relative wage. This curve is constructed graphically in Figure 1.

In the right panel the labour market is depicted. An exogenous relative supply is equated to a relative demand that is conditional on n_H/n_L. Two relative demand curves have been drawn and were labelled Z_1 and Z_2, where Z_2 represents a higher ratio of n_H/n_L. By plotting the equilibrium wages against the corresponding values for n_H/n_L one obtains the *PMA*-curve in the left panel. Intuitively this curve is upward sloping as the employment level *per variety* is negatively related to the relative number of varieties per range and therefore positively to the relative marginal value product.[13]

Figure 1: Graphical Construction of the *PMA*-curve



The figure also illustrates the impact of an increase in relative labour supply. For every n_H/n_L the relative wage now drops. Consequently an increase in relative supply, L_H/L_L, will cause the *PMA*-curve to rotate down and to the right as is illustrated in the left panel.[14]

So far the model has closely followed the models by for example Grossman and Helpman (1991a) and Acemoglu (2002). As in these models we can now introduce technical change in the form of adding new varieties to either range of goods.

[13] It is concave because demand is convexly downward sloping in the relative wage. Hence an ever-larger increase in n_H/n_L is required to push relative demand out and relative wages up by the same percentage. This is easily verified by solving (1) for relative wages. The exponent on n_H/n_L is less than 1.

[14] Note that the short-run elasticity of substitution between high and low skilled labour can be derived and is strictly negative. Its absolute value is given by, $\sigma_{SR}\equiv 1/(1-\alpha\beta)$. This expression is identical to the elasticity of substitution in the Acemoglu (2002) model. It also corresponds to the Grossman and Helpman (1991a) that assumes constant returns to labour (β=1).

The Value of Innovations

Assume that innovations can be patented and patents are perfectly enforced. In the absence of a product life cycle the value of a patent that adds a new variety to either range is equal to the discounted (expected) real profit flow that can be generated by it:[15]

$$\frac{v_S(t)}{P(t)} = \int_t^{\infty} e^{-r(t-\tau)} \frac{\pi_S(\tau)}{P(\tau)} d\tau \tag{12}$$

where v_S denotes the value of the patent establishing a new good in variety range n_S and argument *i* has been dropped due to symmetry within the ranges. Equation (12) can be rewritten if we assume constant (expected) growth rates for profits and the price index:

$$v_S(t) = P(t)\frac{\pi_S(t)}{P(t)} \int_t^{\infty} e^{-(r-\dot{\pi}/\pi+\dot{P}/P)(t-\tau)} d\tau = \frac{\pi_S(t)}{r - G_{\pi_S} + G_P} \tag{13}$$

where G_X is the growth rate of *X*. If there is a product life cycle, however, the pricing of patents is more complex. A product life cycle distinguishes between "new" and "mature" products, where the former are produced using high and the latter using low skilled labour, respectively. New products become mature when the production process is changed to allow low skilled labour to step in. I will assume, however, that the product specifications do not change in that transition. For future reference I therefore label the invention of a new product "product innovation", while referring to the creation of a new process that matures an existing product as "process innovation".

When a process innovation now moves a variety from the high to the low skilled range of goods, the profit flow for the high skilled labour using firm abruptly ends. In a closed economy model with perfect patent protection the inventor of the process will have to pay the incumbent firm to obtain the patent for the product.[16] Obviously the incumbent producer is only willing to sell his patent if the price compensates him for the profit flow he foregoes. Since the inventor of the new process can reduce costs and increase profitability, his willingness to pay will exceed the price of the patent. The value of a process innovation however equals the positive *difference* between the present value of a new and that of a mature product's flow of rents. Because compensation is ensured, the value of a product innovation remains given by (13). To introduce the possibility of a life cycle a switch parameter λ that takes value 1 for a product life cycle and 0 otherwise can be introduced and one obtains for the general case:

$$v_H(t) = \frac{\pi_H(t)}{r - G_{\pi_H} + G_P} \quad \text{and} \quad v_L(t) = \frac{\pi_L(t)}{r - G_{\pi_L} + G_P} - \lambda \frac{\pi_H(t)}{r - G_{\pi_H} + G_P} \tag{14}$$

[15] The usual way of thinking about innovation in these models is to assume perfect patent protection. The patent then yields a return in the form of future profit flows and the R&D investment required can be financed by selling such assets. One could also think of an entrepreneur who needs to finance the initiation of a new firm. In that case R&D can be interpreted as non-production labour required for starting up a firm and finding a niche in the market. To finance such up-front investments the entrepreneur must sell his future profits as assets. The return on assets must be equal to *r* in equilibrium for consumers to be willing to finance investment.

[16] In the traditional two-country life cycle models such as Grossman and Helpman (1991a) the assumption of failing patent protection abroad implies that the probability of replacement adds to the effective discount rate in Equation (13).

The Production of Innovations

With a slight abuse of terminology I will assume that product innovation requires the R&D sector to engage in "Research", whereas process innovation requires "Development". The output of the R&D sector is therefore a flow of product and process innovations that I assume can be auctioned off and yield the values derived above. Now consider the following production functions for "Research" and "Development":

$$\begin{aligned} \dot{n} &= n^{\varphi} n_H^{(1-\varphi)\chi} n_L^{(1-\varphi)(1-\chi)} a_R R_R^{\gamma} + (1-\lambda)\dot{n}_L \\ \dot{n}_L &= n^{\psi} n_H^{(1-\psi)\zeta} n_L^{(1-\psi)(1-\zeta)} a_D R_D^{\gamma} \\ n_H &\equiv n - n_L \\ \dot{n}_H &= \dot{n} - \dot{n}_L \end{aligned} \quad \text{where} \quad \begin{aligned} 0 < \gamma \le 1 \\ 0 \le \varphi \le 1 \\ 0 \le \chi \le 1 \\ 0 \le \psi \le 1 \\ 0 \le \zeta \le 1 \end{aligned} \qquad (15)$$

Once more the switch parameter λ was used to distinguish between the product life cycle and the symmetric specification.[17] In a product life cycle specification (λ=1) any addition to range n_L implies a reduction in range n_H and only Research can increase the total number of varieties, n. In a symmetric model the two ranges merely add up to n but can be increased independently. R is the amount of R&D labour allocated to Research, R_R, and Development, R_D, respectively.[18]

The parameters φ, ψ, χ, and ζ define a general Cobb-Douglas knowledge spillover structure, where the number of varieties proxies for three types of knowledge accumulated in previous R&D activity. In Equation (15) one can distinguish *intra-sectoral*, $(1-\psi)(1-\zeta)$ and $(1-\varphi)\chi$, *cross-sectoral*, $(1-\psi)\zeta$ and $(1-\varphi)(1-\chi)$, and *joint*, φ and ψ, knowledge spillovers. Such knowledge spillovers are what drive any endogenous growth model.[19] Note also that, despite the aggregate increasing returns to scale, this specification allows for diminishing returns to R&D resources by allowing for $\gamma \le 1$.

A competitive R&D sector now allocates the available R&D workers, R^*, between these two activities to maximise profits by setting:

$$\frac{R_R}{R_D} = \left(\frac{n_H}{n_L}\right)^{\frac{(1-\psi)\zeta-(1-\varphi)\chi}{\gamma-1}} \left(1+\frac{n_H}{n_L}\right)^{\frac{\psi-\varphi}{\gamma-1}} \left(\frac{v_L}{v_H}\right)^{\frac{1}{\gamma-1}} \left(\frac{a_R}{a_D}\right)^{\frac{1}{1-\gamma}} \qquad (16)$$

The R&D sector thus produces a flow of product and process innovations by employing all available R&D resources and using the public knowledge base accumulated in the past. R&D can be financed using savings as long as the return on R&D investments exceeds or equals the subjective discount rate.

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[17] Setting λ=0, ζ=(1-δ)/2, γ=1, χ=(1+δ)/2, φ=0, ψ=0, yields the Acemoglian (2002) structure. Setting λ=1, ζ=0, γ=1, χ=0, φ=1, ψ=0 yields Grossman and Helpman's (1991a) specification. This does not imply that the model is equivalent to theirs for these parameters, only the innovation functions are. In the original Grossman and Helpman (1991a) model there is no perfect patent protection and international immobility of labour. The original Acemoglu (2002) model has labour and a variety of intermediates combine into homogenous final output whereas here labour produces a variety of final output directly. This causes a slightly different relative profit and hence innovation value functions but with similar characteristics.

[18] The mathematics are much more complicated and little insight is gained by requiring the R&D sector to compete for high skilled labour with production. See Sanders (2004) for a digression in that direction.

[19] See Jones (1995, 2005) for an elaboration of the role of knowledge spillovers in endogenous growth theory. The Cobb-Douglas structure was chosen to simplify the mathematics and is not based on empirical evidence. Jaffe and Caballero (1993) for example suggest that the implied constant returns to accumulated knowledge may be too optimistic and depreciation rates of knowledge, in particular in the 80s, may be high.

The Steady State Equilibrium

Now consider the conditions for a steady state equilibrium. For a given relative supply of high over low skilled labour Equation (10) shows that a stable ratio n_H/n_L implies stable relative wages. Stable relative wages imply stable relative profits, which in turn imply stable relative patent values. Stable relative patent values and a stable ratio n_H/n_L yield a stable allocation of R&D resources that can produce stable growth rates for the two ranges of goods. Hence a stable ratio n_H/n_L is the first condition for a steady state equilibrium. That implies:

$$\frac{\dot{n}}{n}=\frac{\dot{n}_H}{n_H}=\frac{\dot{n}_L}{n_L} \tag{17}$$

using Equation (15) that condition also implies for the steady state allocation of R&D labour that it must satisfy both Equation (16) and:

$$\frac{R_R}{R_D}=\left(\frac{n_H}{n_L}\right)^{\frac{(1-\psi)\zeta-(1-\varphi)\chi}{\gamma}}\left(1+\frac{n_H}{n_L}\right)^{\frac{\psi-\varphi}{\gamma}}\left(\lambda+\frac{n_H}{n_L}\right)^{\frac{1}{\gamma}}\left(\frac{a_R}{a_D}\right)^{\frac{-1}{\gamma}} \tag{18}$$

Setting this expression equal to Equation (16) and solving for relative wages yields a steady state relationship between relative wages and n_H/n_L that, together with the *PMA*-curve, determines all feasible steady state equilibria:[20]

$$\frac{w_H}{w_L}=\left(\frac{b_H}{b_L}\right)^{\frac{1}{\beta}}\left(\lambda+\left(\frac{n_H}{n_L}\right)^{\frac{(1-\varphi)\chi-(1-\psi)\zeta}{\gamma}}\left(1+\frac{n_H}{n_L}\right)^{\frac{\varphi-\psi}{\gamma}}\left(\lambda+\frac{n_H}{n_L}\right)^{\frac{\gamma-1}{\gamma}}\left(\frac{a_R}{a_D}\right)^{\frac{1}{\gamma}}\right)^{\frac{1-\alpha\beta}{\alpha\beta}} \tag{19}$$

This relationship can be labelled the Research and Development Arbitrage curve or *RDA*-curve as it traces out the combinations of relative wages and n_H/n_L for which the R&D sector has no incentive to reallocate resources and both goods ranges grow at the same rate. Relative wages enter this relation through relative profits, which affect the relative value of innovations. The relative range, n_H/n_L, also enters through the knowledge spillovers assumed in the innovation function. Figure 2 shows the three basic shapes that the *RDA*-curve can have around a steady state, convex downward sloping, concave upward sloping and finally convex upward sloping. With strong intra-sectoral knowledge spillovers the curve is upward sloping. Higher relative wages are required in equilibrium to reduce the incentive to invest R&D resources in the sector with the larger knowledge base. If knowledge spillovers are also cross-sectoral, however, lower relative wages are required to offset the incentive to invest R&D resources in the smaller sector.

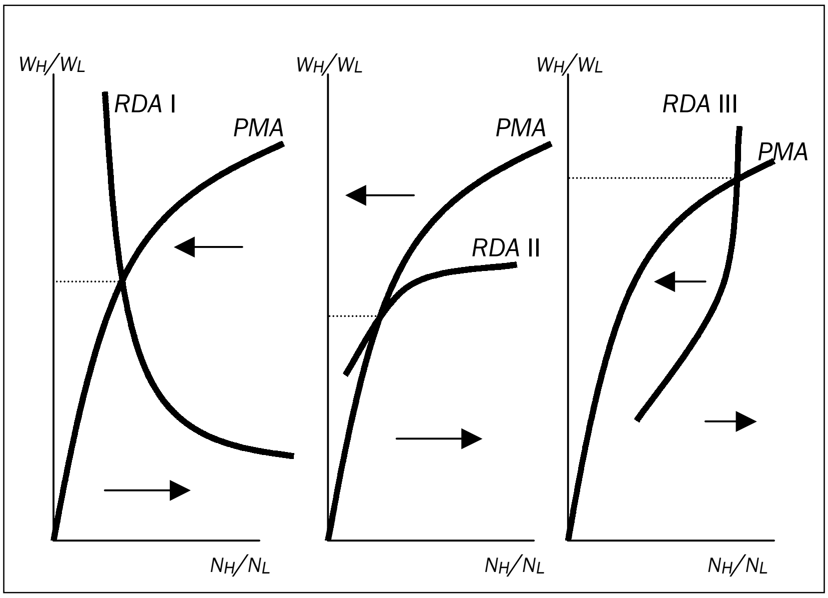
The arrows indicate the direction in which n_H/n_L will change when one starts in a point off the *RDA*-curve. Below the *RDA*-curve n_H/n_L will grow. The intuition is quite straightforward. In that situation relative wages are, given the available knowledge stocks, too low. Consequently relative profits are too high and this provokes too much investment in high skilled complementary innovation, causing n_H/n_L to rise.[21] Hence the

[20] Note that the fact that profits grow at the same (negative) rate in both ranges in the steady state was used to eliminate the ratio of discount rates from the ratio of patent values.

[21] Krugman (2000) uses and refers to this intuitive type of dynamics analysis as ad-hoc dynamics. Proofs and derivations are left for the Appendix.

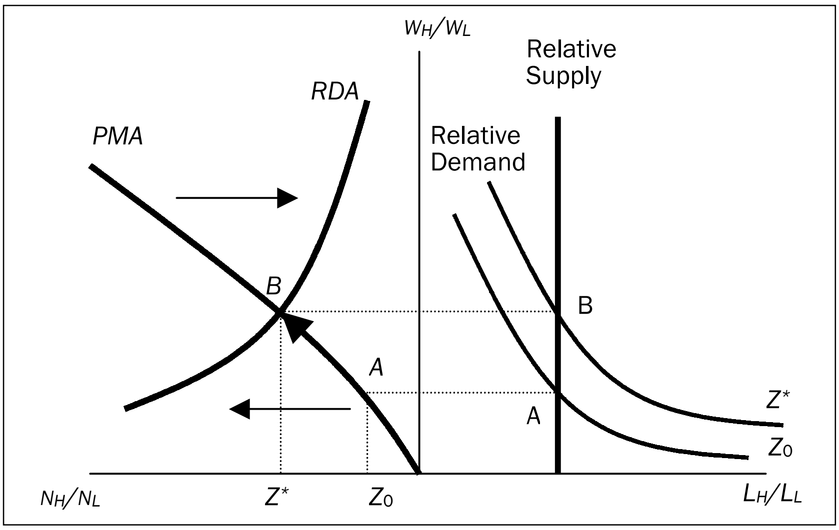
equilibrium is only stable if the *RDA*-curve intersects the *PMA*-curve from above as has been verified more formally in the Appendix.

Figure 2: The Shapes of the *RDA*-curve



Combining Figures 1 and 2 yields the complete model in Figure 3. Starting from a point such as *A* in the right panel, the corresponding position on the *PMA* relative to the *RDA*-curve determines that n_H/n_L will grow. As n_H/n_L increases, the relative labour demand curve in the right panel shifts out and relative wages increase. In the left panel the economy moves up along the *PMA*-curve. This process stops and the model is in steady state equilibrium when the intersection of *PMA* and *RDA* is reached at points *B*.

Figure 3: Steady State Equilibrium



Section 2: Analysis of the Equilibrium

Now consider the two hypotheses formulated in the introduction. As was shown in Figure 1, the *PMA*-curve rotates downward if the relative availability of skilled labour rises. In the adjustment to the new steady state n_H/n_L will rise, reflecting that Hicksian induced innovation occurs in the model whatever type of *RDA*-curve prevails. For the steady state relative wage to rise, however, the *RDA*-curve must be of type II, concavely upward sloping. This is both a necessary and sufficient condition for the market size effect to arise.

On the other hand the acceleration hypothesis yields unambiguous results in a product life cycle specification only. Without it there is no reason to assume that a new GPT affects one R&D activity more or less than the other. Hence innovation in both ranges would accelerate symmetrically, causing no shifts in the relative wage. Under the product life cycle, however, a new GPT must affect product innovation first. Before a low skilled worker can benefit from say working with a new computer controlled assembly robot one must first design and produce and debug etc. etc. the robot itself. In the PLC-model, therefore, productivity in product innovation will rise before any rise in process innovation can occur. The introduction of a GPT can thus be represented by a rise in a_R/a_D. Equation (19) shows that that rise will unambiguously shift the *RDA*-curve out. If the productivity shock were permanent, the new steady state would have higher n_H/n_L and w_H/w_L. But even when the shock is temporary relative wages rise for as long as the productivity effect is present.

In the model presented above both alternative hypotheses thus have different necessary and sufficient conditions. The necessary and sufficient condition for the market size effect is the condition that the RDA-curve is of type II. The conditions for the acceleration hypothesis are the existence of the product life cycle and the introduction of a GPT that affects productivity in R&D asymmetrically. Let us now consider them in turn and confront both hypotheses with the evidence available.

The Market Size Hypothesis

In the Appendix it is shown that the *RDA*-curve is Type II and therefore the market size effect exists in a non-PLC model iff:

$$1-\gamma \le (1-\varphi)\chi-(1-\psi)\zeta+(\varphi-\psi)\frac{n_H/n_L}{1+n_H/n_L} \le 1-2\gamma+\sigma_{SR}\gamma \qquad (20)$$

The window of opportunity for the market size hypothesis is thus limited by strong diminishing returns in R&D, low γ, and a low (absolute) elasticity of substitution between high and low skilled in the short run ($\sigma_{SR} \equiv |d(L_H/L_L)/d(w_H/w_L)*(w_H/w_L)/(L_H/L_L)|=1/(1-\alpha\beta)$. Given these parameters, intra-sectoral spillovers must exceed cross-sectoral spillovers in innovation although the impact of joint spillovers is mixed and may compensate. Lacking evidence or intuition on the knowledge spillovers in the non-PLC specification, they can be set symmetrically. Setting $\varphi=\psi$, and $\chi=(1-\zeta)=(1+\delta)/2$, yields:

$$1-\gamma \le \delta \le 1+(\sigma_{SR}-2)\gamma \qquad (21)$$

where $0<\delta<1$ represents the degree of intra-versus cross-sectoral spillovers and (21) yields results that are comparable to those of Acemoglu (2002) for $\gamma=1$. An empirically plausible range for the elasticity of substitution is $1 \le \sigma_{SR} \le 2$, then yields quite a reasonable range for δ and no a priory reasons exist to dismiss the market size effect.[22] It can be verified in (21) however, that diminishing returns in R&D could seriously challenge that conclusion. As γ falls so does the window for the strong market size effect.[23]

Nadiri (1993) surveys the available evidence on this parameter for the late 70s and early 80s. Contributions by for example Griliches (1979, 1984), Mansfield (1980, 1984) and Jaffe (1986, 1988) come up with estimates between 0.2 and 1. Although this suggests that diminishing returns are likely, Nadiri (1993) argues that the evidence is inconclusive, as several empirical problems bias the estimates downwards.[24] Most of the literature, however, estimates the R&D production functions using observed R&D expenditures as inputs and patents as outputs. The crude elasticity thus obtained is seriously biased if wages reflect marginal productivity and labour accounts for the bulk of R&D expenditure (as in the model above). To see this assume the model above describes reality. Estimating the real output elasticity would require estimating an equation like:

$$\log(\#\, patents_t) = \beta_0 + \beta_1 \log(R_t) + u_t \qquad (22)$$

where $\hat{\beta}_1$ is an unbiased estimator of γ.[25] Now consider estimating:

$$\log(\#\, patents_t) = \beta_0 + \beta_1 \log(w_{Rt} R_t) + u_t \qquad (23)$$

where we know that w_R is a function of $R^{\gamma-1}$ given by the first order conditions for profit maximisation in R&D. Then we estimate:

$$\log(\#\, patents_t) = \beta_0 + \beta_1 \gamma \log(R_t) + u_t \qquad (24)$$

and the estimated coefficient will over- or underestimate the true γ if $\gamma<1$.[26] Running a regression like (22) using the (log) number of new products at the 2 digit standard industry classification reported in the Community Innovation Survey of 1996 for the Netherlands and (the log of) full time equivalents reported in R&D for that sector, yields an elasticity of 0.4-0.5.[27] Those values correspond nicely with results obtained by Acs and Audretsch (1988) and Blundell et al. (2002) for the US and Jacobs, Nahuis and Tang (2002) for the Netherlands in similar direct regressions of this output elasticity.

With that range for the output elasticity in R&D the window for the market size hypothesis is closing rapidly. It implies, using γ=0.5 and σ_{SR}=2:

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22 Freeman (1986) surveyed the evidence on the short run elasticity of substitution and concludes between 1 and 2 is most likely, although values exceeding as much as 8 have been reported.

23 The condition in Equation (21) is not found in exactly this form in Acemoglu (2002) as a slightly different set-up of the model is used. Acemoglu (2002) distinguishes intermediate and final good production and the bang-bang nature of the equilibrium in R&D causes a horizontal *RDA*-curve. The analyses here is therefore not a generalisation in the proper sense.

24 For example he points out that the quality of R&D output may have risen and there may be issues concerning the over-reporting of R&D expenditures for tax reasons. Both would cause a negative bias. Authors that have corrected for these things, however, find higher estimates but remain below 1.

25 In the literature the variation over industries or firms is also used to identify the parameters.

26 The intuition is that the average of squared observed gamma's in the data will exceed the average of the observed gamma's if some of the observed γ>1. If all γ<1 than this estimation will underestimate the true output elasticity. That may help explain the wide range 0.2-1.0 found in the literature.

27 Controlled for 1-digit industry fixed effects. The data used are discussed in detail in Van Zon and Sanders (2002), although this particular regression has not been published.

$$0.5 \leq (1-\varphi)\chi - (1-\psi)\zeta + (\varphi-\psi)\frac{n_H / n_L}{1+n_H / n_L}(=\delta) \leq 0.75 \tag{25}$$

Equation (25) illustrates that in a non-PLC model the knowledge spillover parameters determine the existence of market size effects. And although diminishing returns to R&D labour and low elasticities of substitution impose sever restrictions on these parameters, the market size effect cannot be ruled out at this stage. Further empirical research is required to establish the likely knowledge spillover structure when R&D can engage in high and low skilled complementary research. Elaborate data-analysis using patenting and citations along the lines of Jaffe and Trajtenberg (2002) are promising in this respect, although distinguishing between types, for example between skilled and unskilled labour using innovations, will prove to be a daunting empirical exercise.

Intuition provides more guidance in setting the knowledge spillover parameters in a product life cycle context. In a product life cycle setting it is intuitively reasonable to assume:

$$\begin{aligned} &\varphi > 0.5 > \psi \\ &(1-\psi)\zeta > (1-\varphi)\chi \end{aligned} \tag{26}$$

The elasticity of the *RDA*-curve with respect to n_H/n_L can still be computed and must lie between 0 and 1 for the *RDA*-curve to be of type II. The non-linearities that the product life cycle introduces in the pricing of patents, however, imply that that elasticity is now a complex function of n_H/n_L. For there to be any upward-sloping part in the *RDA*-curve, it can be shown that:

$$\varphi - \psi > (1-\gamma) + \left((1-\psi)\zeta - (1-\varphi)\chi\right) \tag{27}$$

must hold.[28] However, the domain for which the *RDA*-has an upward slope is now limited to:

$$\frac{n_H}{n_L} > \frac{(1-\psi)\zeta - (1-\varphi)\chi}{\gamma - 1 + \varphi - \psi + (1-\varphi)\chi - (1-\psi)\zeta} \tag{28}$$

and only on part of that domain will the curve be concave. Under the PLC specification it is therefore even less likely (but not impossible) that a concave upward slope is relevant for the initial, the final and all transitional values of n_H/n_L, which the market size hypothesis requires. Once more the market size hypothesis cannot be ruled out and further empirical work is required.

In addition to the proposed identification of knowledge spillover structures another and more direct test would be to establish the persistence of initial skill bias. Introducing controls for the product life cycle stages and finding them insignificant in explaining the skill intensity of labour demand over time would strengthen the case for induced innovation in general and the market size effect in particular. The available evidence, however, is not favourable. The evidence in for example Greenwood and Yorukoglu (1997) generally supports the product life cycle. There is strong evidence for the decline in skill intensity over time, following the adoption of new technologies. Moreover

[28] Proof is in the Appendix. Note also that the Grossman and Helpman (1991a) model satisfies this condition and generates the international equivalent of the market size effect. See also Sanders (2004).

Greenwood and Yorukoglu (1997) argue convincingly that innovation accelerated and the demand for skilled labour rose following the introduction of ICT in the late 1970s. They also point out that a lot of small productivity enhancing innovations typically follow the adoption of such radically new technologies. All this evidence therefore strongly supports the acceleration hypothesis to which we now turn.

The Acceleration Hypothesis

The acceleration hypothesis starts from the assumption that a new GPT causes technical change to accelerate. In the model this acceleration can be prompted by temporarily increasing a_R and a_D, the productivity of labour in R&D. The underlying idea is that a new GPT affects innovation in much the same way as an increase in knowledge spillovers.

In the non-PLC specification it would be strange to argue that the GPT favours one type of innovation over the other. In fact the whole idea in this paper is to explain and not assume skill bias in innovation. In the non-PLC model the shock would therefore have to be symmetric. It can be verified in Equation (19) that an increase in both a_R and a_D will not shift the *RDA*-curve and therefore the same relative wage will prevail at accelerated rates of innovation.

However, with the product life cycle in mind, an asymmetric productivity shock becomes much more acceptable and indeed likely. As Greenwood and Yorukoglu (1997) (and many others before them, see for example Hirsch (1965)) have shown, the introduction of a new technology is typically followed by a gradual process of diffusion and adoption. The fact that it takes time to adopt a new technology implies there are costs, both of the informational and monetary nature. The going operations need adaptation, people have to learn and knowledge needs to be developed and obtained.

As the learning process continues the goal gradually shifts from increasing quality and reliability to catering to customer needs to reducing production costs. In that later stage expensive high skilled labour is gradually phased out of production and/or complemented with a lot of specialised physical capital. Productivity picks up as bias is reduced.[29] Hence in the context of the model a GPT will increase the productivity of what I refer to as Research, whereas that of Development will follow endogenously. The latter is captured by the large cross-sectoral knowledge spillover that increases as n_H/n_L rises in response to the initial productivity shock that affected only Research.

The case for the acceleration hypothesis now rests on two sufficient and necessary conditions First productivity in R&D must have shifted asymmetrically over the 80s in favour of product innovation and second the product life cycle must exist. Finding the product life cycle significant is therefore a first step in establishing the acceleration hypothesis as it was put forward in this paper. The second step would be to empirically establish a link between the acceleration in (product) innovation and changing parameters in the (research) innovation function. For the acceleration hypothesis to operate as hypothesised in the model, one would thus have to establish a shift (of the appropriate sign) in the productivity of R&D workers in various types of R&D.

The evidence on the output elasticity, presented by Nadiri (1993), provides a first indication that perhaps the parameters of the innovation functions are not stable over time. If one could establish that the output elasticity has risen and fallen over the eighties, both market size effect and acceleration hypothesis may have had a role to play.[30] Jaffe (1997) also argues that the stock of public knowledge and the rate of knowledge depreciation have followed a distinct cyclical pattern over the last century,

[29] This explains the success of the acceleration hypothesis to explain productivity slowdown during the late 70s and early 80s, but also has implications for the skill biased technical change debate.

[30] Recall that a rise in γ, even if temporary, increases the likelihood of market size effects to occur.

indicating stable dynamics in innovation parameters, that follow the introduction of new GPTs. If an asymmetric shock to labour or total factor productivity in Research relative to Development can be identified, following what Greenwood and Yorukoglu (1997) label the watershed of 1974, then the acceleration hypothesis is likely to contribute to explaining wage divergence in the 80s.

Section 3: Concluding Remarks

The analysis of an endogenous two-type innovation model has provided the micro foundations for two hypotheses that have been proposed to explain skill biased technical change. In evaluating the sufficient and necessary conditions in the unified framework of that model, the market size effect as proposed by Kiley (1999) and Acemoglu (1996, 2000, 2002) is shown to face severe parameter restrictions. The acceleration hypothesis, as proposed by for example Galor and Tsiddon (1997), Galor and Moav (2000), Aghion (2001) and Aghion and Howitt (2002), faces less severe parameter restrictions, but basically requires the model to have a product life cycle specification. The evidence in support of such a specification is mounting but not conclusive. In light of the available empirical evidence both hypothesis can therefore neither be accepted nor rejected and further empirical work needs to be done.

The paper presents a clear empirical research program that may help future research to do so. To make a clear and strong case for either hypothesis, the parameters of the innovation functions require further empirical research. In particular the importance of spillovers between types of innovation determines the fate of both hypotheses. The big challenge will be to separate one type of innovation from the other, but the analysis may proceed in a few steps. If a product life cycle can be established the two types of innovation of interest can be labelled variety or quality enhancing product and cost reducing process innovation. This distinction may also prove empirically useful. Recent surveys on R&D and technology, such as the EU's Community Innovation Surveys explicitly ask for more detail along these lines in their questionnaires.

Furthermore patent citation research along the lines of Jaffe (1997) and more recently Hall and Trajtenberg (2004) may prove useful in distinguishing separable knowledge bases. Their evolution over time can then be used to proxy for productivity shocks that are vital to the acceleration hypothesis. The identification of intra- and cross-sectoral knowledge spillovers that such data would allow is also helpful in making the case for the market size effect.

One might of course also argue that we only have to wait and observe the long-run effects as both hypotheses predict different and easily observable outcomes there.[31] Moreover, temporary shifts in innovation function parameters may very well cause temporary market size effects as was argued above. But perhaps most importantly, if the market size effect plays a role in permanently shifting the relative labour demand curve, the time for policy action is now.[32] And even if it is merely a temporary acceleration, there is no reason to ignore the plight of the low skilled that suffer its consequences.

[31] However, even if that were the preferred strategy, it would be hard to settle the debate on how long it would take the economy to return to a steady state. The evidence in Greenwood and Yorukoglu (1997) for example suggests it might take a truly new GPT over 50 years to fully mature. If within that time a new GPT arrives (bio- and genetic technology for example), the long run equilibrium is never reached.

[32] Especially if endogenous responses, for example in labour supply, strengthen temporary shifts into permanent changes.

Appendix

The Stability of the Steady State Equilibrium

In this appendix it is first shown that the steady state equilibrium is stable if and only if the *RDA*-curve cuts the *PMA*-curve from above. First define, to save on notation, $z \equiv n_H / n_L$. Now it is necessary to prove that in all points in z-w_H/w_L-space that lie below the *RDA*-curve the model predicts an increase in *z* and in those above *z* drops. *z* increases when relative efforts in R&D exceed those in a stable equilibrium. Substitution for patent values in equation (16) yields:

$$\frac{R_R}{R_D} = z^{\frac{(1-\psi)\zeta-(1-\varphi)\chi}{\gamma-1}} (1+z)^{\frac{\psi-\varphi}{\gamma-1}} \left(\lambda + \varepsilon \frac{\pi_L}{\pi_H}\right)^{\frac{1}{\gamma}} \left(\frac{a_R}{a_D}\right)^{\frac{1}{1-\gamma}} \tag{A1}$$

in and out of equilibrium, where $\varepsilon \equiv (r - G_{\pi_H} + G_P)/(r - G_{\pi_L} + G_P)$. *z* increases when this ratio exceeds the stable ratio in Equation (18):

$$\frac{R_R}{R_D} = z^{\frac{(1-\psi)\zeta-(1-\varphi)\chi}{\gamma}} (1+z)^{\frac{\psi-\varphi}{\gamma}} (\lambda + z)^{\frac{1}{\gamma}} \left(\frac{a_R}{a_D}\right)^{\frac{-1}{\gamma}} \tag{A2}$$

Substituting for profits in Equation (A1) using equations (9) and (11) one obtains, after some tedious rewriting, that *z* will rise iff:

$$\begin{aligned} & z^{\frac{(1-\psi)\zeta-(1-\varphi)\chi}{\gamma-1}} (1+z)^{\frac{\psi-\varphi}{\gamma-1}} \left(\lambda + \varepsilon \left(\frac{w_H}{w_l}\right)^{\frac{\alpha\beta}{1-\alpha\beta}} \left(\frac{b_H}{b_L}\right)^{\frac{\alpha}{\alpha\beta-1}}\right)^{\frac{1}{\gamma}} \left(\frac{a_R}{a_D}\right)^{\frac{1}{1-\gamma}} > \\ & z^{\frac{(1-\psi)\zeta-(1-\varphi)\chi}{\gamma}} (1+z)^{\frac{\psi-\varphi}{\gamma}} (\lambda + z)^{\frac{1}{\gamma}} \left(\frac{a_R}{a_D}\right)^{\frac{-1}{\gamma}} \end{aligned} \tag{A3}$$

holds. Solving for relative wages one obtains:

$$\frac{w_H}{w_L} < \varepsilon^{\frac{\alpha\beta-1}{\alpha\beta}} \left(\frac{b_H}{b_L}\right)^{\frac{1}{\beta}} \left(\lambda + z^{\frac{(1-\varphi)\chi-(1-\psi)\zeta}{\gamma}} (1+z)^{\frac{\varphi-\psi}{\gamma}} (\lambda+z)^{\frac{\gamma-1}{\gamma}} \left(\frac{a_R}{a_D}\right)^{\frac{1}{\gamma}}\right)^{\frac{1-\alpha\beta}{\alpha\beta}} \tag{A4}$$

where the right hand side is equal to the *RDA*-curve times a power of ε. We now know, however, that in any point below this adjusted curve z will rise. As the power is negative the *RDA*-curve should be adjusted downwards (upwards) if ε >1 (ε<1). From the definition of ε we know that this is the case when the growth rate of high skilled profits is smaller than that of low skilled profits, i.e. when relative profits are expected to fall. Using Equations (11), (9) and substituting for relative wages using labour market equilibrium in Equation (10) we can solve for relative profits:

$$\frac{\pi_H}{\pi_L} = z^{-\alpha\beta}\left(\frac{b_H}{b_L}\right)^{\alpha}\left(\frac{L_H}{L_L}\right)^{\alpha\beta} \tag{A5}$$

From this expression it is clear that relative profits can be expected to fall only when z is expected to rise. The ratio of effective discount rates therefore only exceeds 1 when z is expected to rise. We know from Equation (A4) that this expectation can only be rational when for a given z relative wages lie below the downward adjusted *RDA*-curve. Now consider starting in such a point below the downward adjusted *RDA*-curve. As z rises, relative wages increase along the *PMA*-curve. This reduces relative profits (as expected), causing future expected reductions in relative profits to fall as well. Hence ε will fall and the downward adjustment of the *RDA*-curve is reduced. If the *RDA* intersects the *PMA* from above, this process continues smoothly until the long-run equilibrium is reached at the intersection. Otherwise z will tend to 0 or infinity and there is no stable equilibrium. In principle it would be possible that the economy adjusts and finds itself on the PMA but between the *RDA* and the adjusted *RDA*. Then z would fall, pushing the model away from the equilibrium. This situation, however, is inconsistent with rational expectations as the *RDA* curve is adjusted downward *because* relative profits and therefore z are expected to rise. Rational expectations thus ensure smooth adjustment towards the equilibrium and in any point below the *RDA* the allocation of resources in R&D will be such that z rises. Obviously the reverse holds above the *RDA*-curve.

Q.E.D.

Formal derivation of the condition for strong market size effects in the non-PLC model

First consider the general *RDA*-curve in Equation (19). Setting λ=0 and using $z \equiv \frac{n_H}{n_L}$ and $\sigma_{SR} \equiv \left|\frac{d(L_H/L_L)}{d(w_H/w_L)}\frac{w_H/w_L}{L_H/L_L}\right| = \frac{1}{1-\alpha\beta}$ the *RDA*-curve for non-PLC specifications is given by:

$$\frac{w_H}{w_L} = \left(\frac{b_H}{b_L}\right)^{\frac{1}{\beta}}\left((z)^{\frac{(1-\varphi)\chi-(1-\psi)\zeta+\gamma-1}{\gamma}}(1+z)^{\frac{\varphi-\psi}{\gamma}}\left(\frac{a_R}{a_D}\right)^{\frac{1}{\gamma}}\right)^{\frac{1}{\sigma_{SR}-1}} \tag{A7}$$

As was shown in Figure 2 the market size effect only exists in a stable steady state equilibrium when the *RDA* has an upward sloping concave section and cuts the *PMA*-curve from above. The *RDA*-curve is concave upward sloping when the elasticity of (A7) with respect to z lies between 0 and 1. Taking the total derivative with respect to z and dividing by Equation (A7) this condition can be written as:

$$0 < \frac{1}{\sigma_{SR}-1}\left(\frac{(1-\varphi)\chi-(1-\psi)\zeta+\gamma-1}{\gamma} + \frac{z}{1+z}\frac{\varphi-\psi}{\gamma}\right) < 1 \tag{A8}$$

Some rewriting (note that empirical evidence suggests σ_{SR}>1 as is implied by $\alpha\beta$<1) yields equation (20). Q.E.D.

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