The Economic Journal, **106** (*March*), 458–470. © Royal Economic Society 1996. Published by Blackwell Publishers, 108 Cowley Road, Oxford OX4 1JF, UK and 238 Main Street, Cambridge, MA 02142, USA.

THE LOW-SKILL, LOW-QUALITY TRAP: STRATEGIC COMPLEMENTARITIES BETWEEN HUMAN CAPITAL AND R&D*

Stephen Redding

This paper investigates the relationship between investments in human capital and R&D in a model of endogenous growth. Both forms of investment exhibit pecuniary externalities and are, as a result, strategic complements. Multiple equilibria may occur for intermediate parameter values, and the present analysis may be seen as providing a theoretical rationalisation for the idea that an economy may become trapped in a 'low-skills' equilibrium, characterised by a poorly trained workforce and low product quality. In the presence of multiple equilibria, there may be a welfare-improving role for government policy in co-ordinating expectations.

The present paper argues that an economy's deficiencies in education and training may be intimately related to firms' investments in product quality, which, in the present case, take the form of profit-seeking Research and Development (R & D). We present a formal model of endogenous growth in which workers invest in human capital or the acquisition of skills,[1] while firms invest in quality-augmenting R & D. The two forms of investment exhibit pecuniary externalities and are strategic complements. The incentives for both forms of investment are interdependent; both determine the economy's growth rate, and multiple equilibria exist for intermediate parameter values.

The analysis seeks to integrate two strands of endogenous growth theory, one that has emphasised investments in R & D (see for example Aghion and Howitt (1992) and Romer (1990)) and another that has emphasised the accumulation of human capital as an 'engine' of growth (see for example Lucas (1988) and Stokey (1991)).

In terms of empirical evidence, both Lichtenberg (1992) and Coe and Helpman (1993) find that R & D has a significant effect upon growth, while a number of authors including Mankiw *et al.* (1992) and Barro (1991) have found that human capital variables are important. There is some debate as to whether the economy's growth rate depends upon the level or the rate of growth of human capital (see for example Benhabib and Spiegel (1994)), and the present paper argues that it is the accumulation or growth of skills that is important.

However, there is significant empirical evidence that not only can R & D and

* This research was funded by the E.S.R.C. I would like to thank my supervisors, Philippe Aghion and Steve Nickell, for many helpful comments and suggestions. I am especially grateful to Jon Temple for comments, and also to Gavin Cameron, Cecilía Garcia-Peñalosa, Meg Meyer, John Muellbauer, seminar participants in Oxford and Canterbury, and two anonymous referees. Responsibility for opinions and errors lies with the author.

[1] For the purposes of the present paper, we make the standard assumption that the education, training and skills of an economy's workforce may be represented by an aggregate stock of human capital H. Hence, the terms education, training, skills and human capital will be used interchangeably. The many interesting issues concerning the heterogeneity of skills are left to one side.

human capital explain growth, but that the incentives to invest in each are interdependent. In a comparative study of clothing manufacture, Steedman and Wagner (1989) cite differences in workforce skills or training as one major explanation for the greater innovativeness of German firms: 'In the course of their two or three-year training the German machinists had mastered the whole range of operations required for garment making; consequently, when a new style was to be made they needed only a short time (an average of two days) to reach 100 per cent speeds.... Only a small minority of machinists in the British plants visited had mastered more than a few basic operations during their shorter training; not surprisingly, much longer periods (several weeks on average) were required.'[2]

Finegold and Soskice (1988) argue that Britain is trapped in a 'low-skills' equilibrium, that is, 'a self-reinforcing network of societal and state institutions which interact to stifle the demand for improvements in skill levels'.[3] Firms' investments in R & D (and hence implicitly their choice of technology) and workers' investments in acquiring human capital are two aspects of this network of institutions. The strategic complementarities between these two forms of investment, and the multiple equilibria that result in the presence of fixed costs, are seen as providing a theoretical rationalisation for Finegold and Soskice's claims, and one that is consistent with rational, optimising behaviour.

Section I presents a formal model, and derives the main results of the paper and the economy's steady-state rate of growth. In Section II, we examine some policy implications, and, specifically, the role for welfare improving R & D and educational subsidies. Section III concludes.

I. THE MODEL

Acemoglu (1994) examines a model in which entrepreneurs and workers undertake private investments (in physical and human capital respectively) in the context of labour market search. Pecuniary externalities exist and multiple equilibria may result in the presence of unemployment. A subsection of the paper examines a static choice between two technologies, a case that is similar to Snower (1994), who considers a static choice between skilled and unskilled vacancies.

The present analysis shows that a search theoretic framework that follows Acemoglu (1994) is capable of explaining the empirical evidence on human capital and R & D discussed above. We combine a model of human capital accumulation in the context of labour market search with a 'quality ladder' model of R & D that follows Aghion and Howitt (1992). We thus seek to investigate the relationship between investments in human capital and R & D in an explicitly dynamic model of endogenous growth.

[2] Steedman and Wagner (1989), p. 49.
[3] Finegold and Soskice (1988), p. 22.

I.1. *The Basic Setup*

I.1.1. *Workers*

We assume that the world is populated by a sequence of non-overlapping generations. Generations are indexed by t, and each consists of a continuum of workers indexed by l of mass L (normalised to 1) and a continuum of entrepreneurs indexed by i of mass N (normalised to 1). Agents are assumed to live for two periods. Time is indexed by τ, and units of time are chosen such that each period lasts for one unit of time.[4]

Workers are assumed to be risk neutral, and the lifetime utility a worker of generation t is given by,

$$U_t(c_{1,t}, c_{2,t}) = c_{1,t} + \left(\frac{1}{1+\rho}\right) c_{2,t}, \tag{1}$$

where $c_{j,t}$ denotes consumption of generation t in period j, and the interest rate r_t equals the subjective rate of time discount ρ.

At birth, individuals are assumed to inherit a stock of human capital from the preceding generation. This intertemporal spillover of human capital follows Lucas (1988), and the period 1 human capital of a representative worker l of generation t is given by,

$$h_{1,t}(l) = (1-\delta) H_{2,t-1}, \tag{2}$$

where δ denotes the exogenous rate of depreciation of human capital across generations and $H_{2,t-1}$ is the aggregate period 2 stock of human capital of generation $t-1$,[5]

$$H_{2,t-1} = \int_0^1 h_{2,t-1}(l)\, dl. \tag{3}$$

Workers may augment their period 2 stock of human capital by devoting a fraction of period 1 to education or schooling. The timing of decisions is assumed to be as follows. At birth, workers decide upon the fraction ν, $0 \leqslant \nu \leqslant 1$ of period 1 to allocate to schooling or human capital accumulation. Once this decision is made, we assume that each worker is randomly matched one-to-one with an entrepreneur for the duration of their lifetime. Production then occurs for a fraction $(1-\nu)$ of period 1, and throughout period 2.[6]

The education production technology is assumed to be as follows. A worker who devotes a fraction ν of period 1 to education is assumed to acquire the following period 2 stock of human capital,

$$h_{2,t} = (1+\gamma\nu^{\theta})\, h_{1,t}, \quad 0 < \theta < 1, \quad 0 \leqslant \nu \leqslant 1, \quad \gamma > 0, \tag{4}$$

where γ and θ parameterise the productivity of the education technology. As

[4] In order to simplify notation further, we will often suppress an implicit dependence upon time, except where important.

[5] In general, we use upper case letters to denote aggregate values, and lower case letters to denote the corresponding values for representative individuals.

[6] Workers are assumed to be matched with entrepreneurs for the duration of their lifetimes. In terms of Acemoglu (1994), this corresponds to the case of high mobility costs.

a result of the intertemporal spillover noted above, the larger the inherited stock of human capital $h_{1,t} = (1-\delta) H_{2,t-1}$, the more productive investments in human capital accumulation.

I.1.2. *Entrepreneurs*

Each entrepreneur is assumed to produce homogeneous final goods output y with the following constant returns to scale production function,

$$y_{j,t}(i) = A_{j,t}(i)\, h_{j,t}, \quad j = 1, 2, \tag{5}$$

where $A_{j,t}(i)$ denotes the productivity or quality of the technology employed by entrepreneur i in period j,[7] and $h_{j,t}$ denotes the period j human capital of the representative worker employed by entrepreneur i. We choose final goods output for numeraire and hence $p_t = 1$, for all t.

Entrepreneurs may invest in uncertain Research and Development (R & D) to raise the quality of final goods output. Specifically, at the beginning of period 1 entrepreneurs are assumed to decide upon the fraction α of period 1 output to devote to costly R & D. Research takes one period and at the beginning of period 2, the uncertainty surrounding research projects is realised. If research is successful, the entrepreneur enjoys a one-period patent on the new technology, which may be used in production in period 2. At the end of this period, the patent expires, and the research knowledge embodied in it is assumed to spillover to all entrepreneurs.

R & D is plausibly characterised by large sunk costs and indivisibilities, and hence, following Aghion and Howitt (1994), we will be concerned with the case where the costs of research are fixed. We assume that a fixed fraction α' of period 1 output is required to produce a research facility, which then yields innovations according to a stochastic production technology. Thus, if a fraction $\alpha \geqslant \alpha'$ of period 1 output is devoted to research, where $0 < \alpha' < 1$, an entrepreneur successfully innovates with probability ψ, where $0 < \psi < 1$. However, for $\alpha < \alpha'$, the probability of research success is zero. The probability μ that an innovation occurs at the end of period 1 is thus,

$$\mu = \begin{cases} 0 & \text{if} \quad \alpha < \alpha' \quad \text{where} \quad 0 < \alpha' < 1 \\ \psi & \text{if} \quad \alpha \geqslant \alpha' \quad \text{where} \quad 0 < \psi < 1 \end{cases}. \tag{6}$$

Following Aghion and Howitt (1992), we assume that each new technology enables human capital to supply $\lambda > 1$ times as many product services as the previous one. As a result of the spillover of technological knowledge above, all entrepreneurs will employ the same technology in period 1. Normalising starting quality A_0 to 1, the quality of the period 1 technology employed by entrepreneurs of generation t is given by $A_{1,t} = \lambda^m$, where m denotes the number of innovations that have occurred. Technologies may be thought of as steps on a 'quality ladder' and may be indexed by m alone, $m = 0, \ldots, \tilde{m}$, where $\tilde{m}$ denotes the state of the art or highest quality technology. In period 2, technologies will vary across entrepreneurs, according to the distribution of research successes, and we may index the technology of entrepreneur i by $m(i)$.

[7] Quality and productivity are essentially equivalent in this simple framework.

I.1.3. *Wage Determination*

Following Acemoglu (1994), workers and entrepreneurs are randomly matched one-to-one so that no entrepreneur or worker remains unemployed. We assume that the surplus from a match is divided between entrepreneurs and workers in the constant proportions $(1-\beta)$ and β respectively.[8] Hence, the period j wage per unit of human capital received by an employee of entrepreneur i is given by,

$$w_{j,t}(i) = \beta A_{j,m}(i). \tag{7}$$

In period 1, all entrepreneurs enjoy the same technology. When deciding upon the fraction of period 1 to spend accumulating human capital, workers must form an expectation of their period 2 wage. Since there is an equal probability of being matched with each entrepreneur, the expected period 2 wage will simply depend upon the expected fraction of entrepreneurs that successfully innovate. Furthermore, since there is a continuum of entrepreneurs of mass 1, each of which innovates with Poisson probability μ, the expected fraction of entrepreneurs that successfully innovate is simply μ. Hence,

$$\begin{aligned} \mathrm{E}_{m,i}[w_{2,m}(i)] &= \beta \mathrm{E}_{m,i}[A_{2,m}(i)] \\ &= \beta[\mu\lambda + (1-\mu)]\, A_{1,m}. \end{aligned} \tag{8}$$

I.2. *General Equilibrium*

I.2.1. *Workers*

The representative worker maximises intertemporal utility (1) given the inherited stock of human capital (2), the human capital production technology (4) and the following intertemporal budget constraint,

$$c_{1,t} + \left(\frac{1}{1+\rho}\right) c_{2,t} \leqslant w_{1,t}(1-\nu)\, h_{1,t} + \left(\frac{1}{1+\rho}\right) \mathrm{E}_{m,i}[w_{2,t,m}(i)]\, h_{2,t}, \tag{9}$$

where the expected period 2 wage $E_{m,i}[w_{2,t,m}(i)]$ is given by (8). Under the assumption of risk neutrality, this intertemporal maximisation problem corresponds to choosing ν to maximise expected discounted lifetime income. Substituting for $c_{j,t}$ in (1) using the lifetime budget constraint (9), and substituting for $h_{1,t}$, $h_{2,t}$ and $w_{j,t}$ using (2), (4), (7) and (8), we obtain,

$$\max_{\nu} \beta\left[(1-\nu) + \left(\frac{1}{1+\rho}\right)[\mu\lambda + (1-\mu)](1+\gamma\nu^{\theta})\right] A_{1,m}(1-\delta)\, H_{2,t-1}. \tag{10}$$

The first-order condition for (10) yields the equilibrium fraction of period 1 spent accumulating human capital,

$$\nu = \begin{cases} \left[\dfrac{\theta\gamma[\mu\lambda + (1-\mu)]}{1+\rho}\right]^{\frac{1}{1-\theta}} & \text{for } 0 \leqslant \left[\dfrac{\theta\gamma[\mu\lambda + (1-\mu)]}{1+\rho}\right]^{\frac{1}{1-\theta}} \leqslant 1 \\ 1 & \text{for } \left[\dfrac{\theta\gamma[\mu\lambda + (1-\mu)]}{1+\rho}\right]^{\frac{1}{1-\theta}} > 1. \end{cases} \tag{11}$$

[8] This assumption may be justified for example by invoking Nash bargaining between workers and entrepreneurs.

We will be concerned solely with parameter values for which an interior solution $0 < \nu < 1$ exists. The fraction of period 1 spent accumulating human capital is independent of the inherited stock of human capital $(1-\delta) H_{2,t-1}$. Although a larger value of $H_{2,t-1}$ raises the productivity of human capital investments, it simultaneously raises the opportunity cost of making those investments (the wage in the productive sector).

From (11) and (6), workers' investments in human capital do depend crucially upon whether or not entrepreneurs are expected to invest in R & D. Specifically,

$$\nu = \begin{cases} \nu_\psi \equiv \left[\dfrac{\theta\gamma[\psi\lambda + (1-\psi)]}{1+\rho}\right]^{\frac{1}{1-\theta}} & \text{if} \quad \alpha \geqslant \alpha' \\ \nu_0 \equiv \left[\dfrac{\theta\gamma}{1+\rho}\right]^{\frac{1}{1-\theta}} & \text{if} \quad \alpha < \alpha', \end{cases} \tag{12}$$

where $\nu_\psi > \nu_0$.

I.2.2. *Entrepreneurs*

Given the research technology (6), if entrepreneurs engage in research, they will invest the fixed fraction α' of first period output in R & D. The only decision remaining for entrepreneurs is whether or not to engage in research. The representative entrepreneur's expected return from research is given by,

$$V(R) = (1-\beta)\left[(1-\alpha')(1-\nu) + \left(\frac{1}{1+\rho}\right)[\psi\lambda + (1-\psi)](1+\gamma\nu^\theta)\right] A_{1,m} h_{1,t}, \tag{13}$$

where we use the fact that the expected period 2 technology of any individual entrepreneur $A_{2,m(i)} = [\psi\lambda + (1-\psi)] A_{1,m}$, and where from the above $h_{1,t} = (1-\delta) H_{2,t-1}$.

Alternatively, if entrepreneurs do not invest in research and continue to employ the existing technology, they receive an expected return of $V(0)$,

$$V(0) = (1-\beta)\left[(1-\nu) A_{1,m} h_{1,t} + \left(\frac{1}{1+\rho}\right) A_{1,m}(1+\gamma\nu^\theta) h_{1,t}\right]. \tag{14}$$

The incentive to engage in research is given by $V(R) - V(0)$, which will be shown to depend crucially upon workers' expected period 1 investment ν in human capital.

I.3. *Rational Expectations Equilibrium*

We employ the Nash equilibrium solution concept to solve for a rational expectations equilibrium, using (2), (12), (13) and (14). On the one hand (from (12)), workers' total and marginal returns from investing in human capital depend upon whether they expect the entrepreneur to invest in R & D. While, on the other hand (from (13) and (14)), the entrepreneur's decision of whether or not to invest in R & D depends upon her expectation of worker's investments in human capital. The two forms of investment exhibit pecuniary externalities and are strategic complements.

Both entrepreneurs and workers must make their investments before they enter the labour market. Furthermore, as in Acemoglu (1994), labour market search means that the identity of one's production partner is unknown. Ex ante contracts that make one party's investment contingent on the other's are thus infeasible, and, as a result of the aforementioned externalities, market outcomes need not necessarily be socially optimal. Moreover, in the presence of the indivisibilities in the research technology, the strategic complementarity between the two agents' investments may result in multiple equilibria. In a rational expectations equilibrium, expected investments in human capital and R & D will equal their actual values. Two possible kinds of equilibria exist.

I.3.1. *High Growth Equilibrium*

In a high growth equilibrium, workers expect the firm to invest in R & D, and the resultant increase in their expected wage increases their incentive to invest in human capital. In turn, a larger expected stock of human capital raises the expected returns to investing in R & D relative to those of continuing to employ an existing technology, and hence the entrepreneur does indeed invest in R & D.

To establish the existence of such an equilibrium, we suppose first that workers expect firms to invest in R & D, in which case $\mu = \psi$, and then show that, if workers have these expectations, it is optimal to incur the fixed cost of R & D. When $\mu = \psi$, then, from (12), $\nu = \nu_\psi$. For research to be optimal, we require $V(R) > V(0)$. That is, substituting for $h_{1,t}$ in (13) and (14) and cancelling terms in $H_{2,t-1}$ and $A_{1,m}$, we require,

$$\frac{\psi(\lambda-1)}{1+\rho} > \frac{\alpha'(1-\nu_\psi)}{(1+\gamma\nu_\psi^\theta)}. \tag{15}$$

I.3.2. *Low Growth Equilibrium*

In a low growth equilibrium the entrepreneur does not find it profitable to invest in R & D and the sole source of growth is human capital accumulation. Workers expect the firm not to invest in R & D and hence reduce their investments in human capital (relative to a 'high growth' equilibrium) accordingly. At this rate of human capital accumulation, the returns to continuing to employ the existing technology exceed those from investing in the development of the next, thereby validating workers expectations.

The existence of a low growth equilibrium may be established in a directly analogous manner to that used above. If $\mu = 0$, then, from (12), $\nu = \nu_0$. For no research to be optimal, we require $V(R) < V(0)$, or, from the above, substituting for $h_{1,t}$ and cancelling terms in H_{t-1} and $A_{1,m}$, we require,

$$\frac{\psi(\lambda-1)}{1+\rho} < \frac{\alpha'(1-\nu_0)}{(1+\gamma\nu_0^\theta)}. \tag{16}$$

I.3.3. *Existence of Equilibrium*

The high growth equilibrium is characterised by both quality improvements and rapid human capital accumulation, and is hence interpreted as a 'high-skills, high-quality' equilibrium. The low growth equilibrium on the other hand is characterised by no research and a reduced rate of human capital acquisition, and is therefore identified with Finegold and Soskice's 'low-skills' equilibrium.

Inequalities (15) and (16) may both be satisfied simultaneously depending on parameter values, and hence multiple equilibria may exist. We may distinguish three possible cases of the model.

PROPOSITION 1. (*a*) *If*

$$\frac{\psi(\lambda-1)}{1+\rho} > \frac{\alpha'(1-\nu_0)}{(1+\gamma\nu_0^\theta)},$$

there exists a single pure strategy 'High Growth' Nash Equilibrium, in which $\mu = \psi$ *and* $h_{2,t} = (1+\gamma\nu_\psi^\theta)\, h_{1,t}$.

(*b*) *If*

$$\frac{\psi(\lambda-1)}{1+\rho} < \frac{\alpha'(1-\nu_0)}{(1+\gamma\nu_0^\theta)}$$

but

$$\frac{\psi(1-\lambda)}{1+\rho} > \frac{\alpha'(1-\nu_\psi)}{(1+\gamma\nu_\psi^\theta)},$$

there exist two pure strategy Nash Equilibria, the 'High-' and 'Low-growth' Equilibria, characterised by $(\mu = \psi, h_{2,t} = (1+\gamma\nu_\psi^\theta)\, h_{1,t})$ *and* $(\mu = 0, h_{2,t} = (1+\gamma\nu_0^\theta)\, h_{1,t})$ *respectively.*

(*c*) *If*

$$\frac{\psi(\lambda-1)}{1+\rho} < \frac{\alpha'(1-\nu_\psi)}{(1+\gamma\nu_\psi^\theta)},$$

then there exists a single pure strategy 'Low Growth' Nash Equilibrium, in which $\mu = 0$ *and* $h_{2,t} = (1+\gamma\nu_0^\theta)\, h_{1,t}$.

Proof. (*a*) Suppose the contrary is true, namely that $\mu = 0$. ν is determined by (12), substituting for ν in (4) and using (2), we obtain $h_{2,t} = (1+\gamma\nu_0^\theta)(1-\delta)\, H_{t-1}$. However, from (13) and (14), this implies that for the parameter values above $V(R) > V(0)$. R & D is profitable, $\mu = \psi$, and we have a contradiction.

(*b*) Suppose $\mu = 0$, then from (12), (2), (4), (13) and (14), under the parameter restrictions above, $V(R) < V(0)$. However, suppose $\mu = \psi$ then $V(R) > V(0)$.

(*c*) Suppose firms undertake R & D, $\mu = \psi$, then from (12), (2), (4), (13) and (14), under the parameter restrictions above, $V(0) > V(R)$ and we have a contradiction. ∎

The inequalities (15) and (16) may be given an intuitive interpretation.

$\psi(\lambda-1)$ is the expected proportional rate of growth of product quality, and $(1+\gamma\nu^{\theta})$ the growth of human capital between periods 1 and 2. From Proposition 1, for multiple equilibria to exist, we require

$$\frac{\alpha'(1-\nu_0)}{(1+\gamma\nu_0^{\theta})} > \frac{\psi(\lambda-1)}{1+\rho} > \frac{\alpha'(1-\nu_{\psi})}{(1+\gamma\nu_{\psi}^{\theta})}.$$

That is, if workers expect entrepreneurs to invest in R & D, the expected rate of growth of product quality, when discounted, exceeds the ratio of the period 1 fixed cost to the growth in human capital across periods. However, if workers expect entrepreneurs to continue to employ the existing technology, this condition is not satisfied.

From the inequality above, multiple equilibria arise for intermediate values of the fixed cost α' and the size and probability of innovation, λ and ψ. For these parameter values, multiple equilibria occur because of, on the one hand, the strategic complementarity between entrepreneurs' investments in R & D and workers' investments in human capital, and, on the other hand, the indivisibility of R & D costs. For R & D to be profitable we require that workers' investments in human capital be sufficiently large to enable entrepreneurs to cover the fixed costs of research. In the terminology of Azariadis and Drazen (1990), this constitutes a threshold externality.

PROPOSITION 2. *For a 'High Growth' Equilibrium to be possible we require either:*
(*a*) *That the fixed cost parameter α' is sufficiently small;*
(*b*) *That the size of innovations $\lambda > 1$ is sufficiently large;*
(*c*) *That the probability of innovation ψ is sufficiently large;*
(*d*) *That the subjective rate of time discount ρ is sufficiently small;*
(*e*) *That the education productivity parameter γ is sufficiently large;*
(*f*) *That the elasticity of human capital with respect to the time spent in education θ is sufficiently large.*

Proof. (*a*)–(*f*) all follow from inspection of Proposition 1 (*a*) and (12).

I.4. *Steady-State Growth*

As in Aghion and Howitt (1992), the economy's actual rate of growth is a random variable depending upon success in uncertain R & D. Here we consider the average or expected rate of growth of aggregate output between the birth of two generations t and $t+1$, over an interval of time $(\tau, \tau+2)$.

From (5), aggregate final goods output is given by $Y_{1,t} = \int_0^1 A_{1,t,m}(i)\, h_{1,t}(i)\, di$, where $\int_0^1 h_{1,t}(i)\, di = H_{1,t}$. Thus, the expected rate of growth of final goods output may be expressed as,

$$\log\left(\frac{\mathrm{E}_{m,i} Y_{\tau+2}}{Y_{\tau}}\right) = \log\left(\frac{\mathrm{E}_{m,i} Y_{t+1}}{Y_t}\right) = \begin{bmatrix} \log \mathrm{E}_{m,i} \int_0^1 A_{1,t+1}(i)\, di - \log \int_0^1 A_{1,t}(i)\, di \\ + \log \mathrm{E}_{m,i} H_{1,t+1} - \log H_{1,t} \end{bmatrix},$$

where, from (2), (3) and (4), $\mathrm{E}_{m,i} H_{1,t+1} = (1-\delta) H_{1,t} \mathrm{E}_{m,i} \int_0^1 [1+\gamma\nu(i)^{\theta}]\, di$. The expected rate of growth of the stock of human capital between two generations depends simply upon the representative worker's investment in human capital and the depreciation rate. Furthermore, since there is a continuum of entrepreneurs i, of mass 1, and each entrepreneur's probability of innovating is independently distributed, then, from (6),

$$\log \mathrm{E}_{m,t} \int_0^1 A_{1,t+1}(i)\, di = \log\{[\mu\lambda + (1-\mu)]\, A_{1,t}\}.$$

In a rational expectations equilibrium, workers correctly anticipate entrepreneurs' decision of whether or not to invest in R & D, and entrepreneurs expectations of workers' investments in human capital are confirmed. Hence, we may establish the following.

PROPOSITION 3. (*a*) *The economy's average or expected rate of growth in a 'High Growth' Equilibrium is*

$$\log\left(\frac{\mathrm{E}_{m,t}\, Y_{t+1}}{Y_t}\right) = \log[\psi\lambda + (1-\psi)] + \log(1-\delta)\int_0^1 (1+\gamma\nu_\psi^\theta)\, di.$$

(*b*) *In a 'Low Growth' Equilibrium the economy's average or expected rate of growth takes the form,*

$$\log\left(\frac{\mathrm{E}_{m,t}\, Y_{t+1}}{Y_t}\right) = \log(1-\delta)\int_0^1 (1+\gamma\nu_0^\theta)\, di.$$

The economy's steady-state rate of growth is determined both by the rate of human capital accumulation, and by whether or not entrepreneurs invest in profit-seeking Research and Development.

PROPOSITION 4. (*a*) *In both a 'Low Growth' and 'High Growth' Equilibrium, the economy's rate of growth is increasing,* (i) *the smaller the depreciation rate* δ, (ii) *the larger the productivity of education parameter* γ, (iii) *the greater the elasticity of human capital with respect to time spent in education* θ *and* (iv) *the smaller the rate of time discount* ρ.

(*b*) *In a 'High Growth' Equilibrium, the economy's rate of growth is also increasing,* (i) *the greater the probability of innovation* ψ *and* (ii) *the larger the size of innovations* λ.

Proof. (*a*) and (*b*) follow from Proposition 3 and (12). ∎

From (12), (4) and (2), the rate of human capital accumulation across generations is determined partly by δ, γ, θ and ρ and hence all four parameters have a direct effect upon the growth rate in both the 'low' and 'high' growth equilibria. In addition, as a result of the strategic complementarities present in the model, γ, θ and ρ all affect the relative profitability of R & D, and hence have indirect effects upon growth in the high growth equilibrium.

These indirect effects may be responsible for discrete changes in the economy's rate of growth. Suppose, we begin with intermediate parameter values that sustain multiple equilibria, and expectations coordinate upon the 'low growth' or 'low skills' equilibrium. Then, for example, as γ and θ rise the economy's rate of growth will undergo a discrete jump at the parameter values at which the 'high growth' equilibrium becomes the unique pure strategy equilibrium.

II. POLICY IMPLICATIONS

The low-skills equilibrium above is Pareto dominated by its high-skills counterpart. The latter implies both a higher level and rate of growth of National Income and Output. Which of the two equilibria obtains for intermediate parameter values is entirely dependent upon entrepreneurs' and workers' expectations. As a result, there may be a welfare improving role for government policy in coordinating expectations.

PROPOSITION 5. *A small, temporary subsidy s towards the costs of R & D may induce the economy to select the high-skills equilibrium and can be self-financing.*

Proof. See Appendix. ∎

Traditionally, government subsidies of R & D are justified in terms of a divergence between private and social marginal returns. Proposition 5 provides a slightly different justification in terms of equilibrium selection. In this case, a small subsidy of R & D may have large effects upon both the level and rate of growth of output, and upon agents' welfare. Furthermore, these large effects may be achieved through a temporary subsidy.

A similar welfare improving subsidy of human capital accumulation (education and training) exists, and there is some evidence, albeit inevitably only suggestive, that an implicit subsidy of this form may have played a role in Korea's economic development. Wood (1994) notes that 'Korea and Taiwan both greatly raised their literacy rates in the 1950s *prior* to the rapid expansion of labour intensive exports in the 1960s'.[9] Indeed the expansion of secondary and higher education was so rapid that 'educated unemployment' began to appear (Wood (1994), p. 212). One interpretation of this rise in high-skill unemployment is that the expansion of education was initially in some sense 'too rapid' for Korea's state of economic development, nonetheless, the increase in the supply of skills raised entrepreneurs incentives to invest in high-technology rather than traditional sectors and products.

However, it is important to note that a rationale for R & D or education subsidies based upon the coordination of expectations only exists for intermediate parameter values for which multiple equilibria exist. In practice, it may be very hard to determine exactly when this is the case.

III. CONCLUSION

The present paper has presented a dynamic model of endogenous growth in which both the rate of human capital accumulation and the intensity of R & D (measured by ψ) determine the economy's long-run rate of growth. Investments in human capital and R & D are strategic complements, and in the presence of indivisible R & D projects, multiple equilibria arise for intermediate parameter values. In one of these equilibria, workers' investments in human capital are sufficiently large so as to amortise the fixed cost of R & D, while in the other, R & D remains unprofitable.

[9] Wood (1994), p. 7 (my italics).

The two equilibria are interpreted as the 'high-skills' and 'low-skills' equilibria described in empirical work by Finegold and Soskice (1988). The 'high-skills' equilibrium Pareto dominates its 'low-skills' counterpart, and an economy in a 'low-skills' equilibrium will enjoy a lower level and rate of growth of per capita income. Which equilibrium is selected depends entirely upon agents' expectations, and a potential role emerges for government policy in coordinating expectations. This justification only exists for intermediate parameter values; however, there is some suggestive evidence that the public policies towards education pursued in Korea might be justified in these terms.

The present analysis suggests that any explanation of cross-country growth performances should consider the interrelationships between different aspects of the growth process (here investments in education and R & D). Introducing strategic complementarities and indivisibilities in investments allows multiple equilibria to arise, which themselves may provide an additional explanation for differing rates of economic growth.

Nuffield College, Oxford

Appendix

Proof of Proposition 5

Suppose that

$$\frac{\psi(\lambda-1)}{1+\rho}=\frac{\alpha'(1-\nu_0)}{(1+\gamma\nu_0^\theta)}$$

and a 'low-skills' equilibrium is just feasible. Since $\nu_\psi > \nu_0$,

$$\frac{\psi(\lambda-1)}{1+\rho}>\frac{\alpha'(1-\nu_\psi)}{(1+\gamma\nu_\psi^\theta)}$$

and a 'high-skills' equilibrium is also feasible.

Consider a small proportional rate of subsidy of the costs of R & D, $s > 0$. The private costs of R & D are now given by $(\alpha'-s)\,y$, where the total cost of the subsidy is $S = sy$. By assumption

$$\frac{\psi(\lambda-1)}{1+\rho}>\frac{(\alpha'-s)(1-\nu_0)}{(1+\gamma\nu_0^\theta)}$$

and the 'low-skills' equilibrium can no longer be supported. The 'high-skills' equilibrium becomes the unique pure strategy equilibrium.

Suppose the subsidy is financed by a proportional rate of tax ϕ, $0 < \phi < 1$, on entrepreneurs' profits. This tax is levied irrespective of whether the entrepreneur engages in R & D or not and hence does not affect the decision to undertake R & D. In equilibrium, all firms undertake R & D, and, for the subsidy to be self-financing, we require, $\phi V(R) > S$. That is, from (13), rearranging and cancelling terms, we require,

$$\phi(1-\beta)\left\{(1-\alpha')(1-\nu_\psi)+\left(\frac{1}{1+\rho}\right)[\psi\lambda+(1-\psi)](1+\gamma\nu_\psi^\theta)\right\}>s(1-\nu_\psi)[1-\phi(1-\beta)],$$

As $s\to 0$, this inequality must be satisfied.

The subsidy need only be temporary. Once it is removed, then, as long as neither the entrepreneur's nor workers' expectations change, the economy will remain at the 'high-skills' equilibrium. ∎

References

Acemoglu, Daron (1994). 'Search in the labour market, incomplete contracts and growth.' CEPR Discussion Paper, no. 1026, September.

Aghion, P. and Howitt, P. (1992). 'A model of growth through creative destruction.' *Econometrica*, pp. 323–51.

Aghion, P. and Howitt, P. (1994). 'Growth and unemployment.' *Review of Economic Studies*, vol. 61 (3), pp. 477–94.

Azariadis, Costas and Drazen, Allan (1990). 'Threshold externalities in economic development.' *Quarterly Journal of Economics*, pp. 501–26.

Barro, R. (1991). 'Economic growth in a cross-section of countries.' *Quarterly Journal of Economics*, pp. 407–43.

Benhabib, Jess and Spiegel, Mark M. (1994). 'The role of human capital in economic development evidence from aggregate cross-country data.' *Journal of Monetary Economics*, vol. 34, pp. 143–73.

Coe, David and Helpman, Elhanan (1993). 'International R & D spillovers.' NBER Working Paper, no. 4444.

Finegold, David and Soskice, David (1988). 'The failure of training in Britain: analysis and prescription.' *Oxford Review of Economic Policy*, vol. 4, no. 3, pp. 21–53.

Lichtenberg, S. (1992). 'R & D investment and international productivity differences.' NBER Working Paper, no. 4161, September.

Lucas, Robert E. (1988). 'On the mechanics of economic development.' *Journal of Monetary Economics*, vol. 22, pp. 3–22.

Mankiw, N., Romer, D. and Weil, D. (1992). 'A contribution to the empirics of economic growth.' *Quarterly Journal of Economics*, May, pp. 407–37.

Romer, Paul (1990). 'Endogenous technical change.' *Journal of Political Economy*, vol. 98, no. 5, pp. S71–102.

Snower, Dennis J. (1994). 'The low-skill, bad-job trap.' CEPR Discussion Paper, no. 999, September.

Steedman, Hilary and Wagner, Karin (1989). 'Productivity, machinery and skills: clothing manufacture in Britain and Germany.' *National Institute Economic Review*, May, pp. 40–57.

Stokey, Nancy (1991). 'Human capital, product quality and growth.' *Quarterly Journal of Economics*, May, pp. 587–616.

Wood, Adrian (1994). *North–South Trade, Employment and Inequality: Changing Fortunes in a Skill-Driven World.* Oxford: Clarendon Press.