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Interaction Between Endogenous Human Capital and Technological Change

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This paper examines how interaction between endogenous human capital accumulation and technological change affects relative wages and economic growth. Private incentives to invest in human capital finance the employment of skilled labour in the education sector, while non-rival technology is a by-product of the education process. The absorption of new technologies into production is skill intensive, creates skill-biased labour demand, and increases the relative wage of skilled to unskilled labour. In contrast to recent models of endogenous growth, higher rates of technological change and growth may be accompanied by a higher relative wage but lower relative supply of skilled labour. Thus the model provides a theoretical foundation for the empirically observed relation between technological change and relative demand, supply and wages of skilled labour.

I. INTRODUCTION

Rapid change in technology in the 1980's was associated with a sharp rise in the relative wage and a decline in the relative supply of skilled labour. Models of endogenous technological change imply, however, that higher rates of innovation should be associated with more skilled labour and lower relative wages.[1] These models focus on private incentives to innovate, but assume that human capital is either exogenous or accidental (learning by doing).[2] Thus, the literature provides few insights into how endogenous technological change influences private incentives to accumulate human capital through relative wage movements.

This paper has two key elements that allow for interaction between endogenous technological change and the relative supply, demand, and wage of skilled labour. First, the two production sectors in the model differ not only in their skill-intensity, but also in technological sophistication. This generates strong skill-biased labour demand and higher relative wages in response to higher rates of technological change. Second, skilled labour is assumed to be an essential input in education, research, and in the absorption of innovations into production. The absorption of bursts in technological change then requires the withdrawal of skilled labour from research and education which subsequently increases the costs of both human capital investment and innovation. We term the resulting leveraging of the future rate of technological change and human capital the *absorption effect*.

1. E.g. Romer (1990), Grossman and Helpman (1991), Aghion and Howitt (1992), and Young (1993).
2. The one exception is Grossman and Helpman (1991, Ch. 5.2), which will be discussed below.

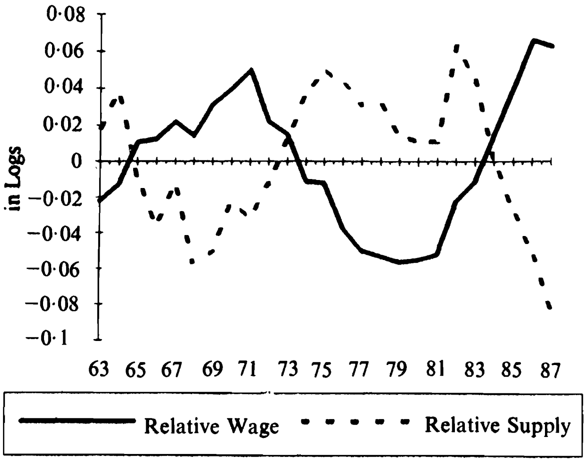

FIGURE 1

Detrended relative supply and wage of College/High School graduates

Source: Katz and Murphy (1992).

This absorption effect provides a novel explanation for empirically observed variations in the relative demand, supply, and wage of skilled labour. Along transition paths, it generates oscillatory interaction between the relative wage and relative supply of skilled labour. Along stationary growth paths the model accounts for the peculiar characteristics of relative demand, supply, and wage of skilled labour in the 1980's. That is, bursts in technological change (such as the computer revolution) can lead to a higher growth path, one characterized by a higher relative wage and *increased* relative demand, but *decreased* relative supply of skilled labour. However, our results are more general. We show that movements in the supply, demand and relative wage of skilled labour depend on the *channel* that promotes higher technological change. If the economy experiences an increase in the productivity of unskilled labour, higher rates of growth and technological change can be accompanied by *lower* relative wages. Less skilled labour is then required to absorb new technology. This depresses the relative wage and allows for a reallocation of skilled labour to research and education.

Interaction between technological change and incentives to accumulate human capital has been well documented in the empirical literature. Katz and Murphy (1992) show that the relative wage and supply of skilled labour have been oscillating, or fluctuating *in an inverse relation to each other*, since at least 1963 (Figure 1).[3] Especially in the 1980's, technological change generated strong skill-biased labour demand that accounted for much of the relative wage movements.[4] Mincer (1994) resolves the apparent supply paradox, namely why skilled labour supply declined in the wake of higher relative wages and increased skill-biased demand. He explicitly considers the *direct cost* of education as a determinant of labour supply and finds a negative correlation between the two since 1967. Our above described absorption effect provides a unified explanation for the dramatic increase in the cost of schooling in the 1980's, the strong skill-biased labour demand and the oscillating supply, demand and relative wage of skilled labour. To no surprise, the

3. OECD (1993) confirms the same pattern for 11 of 17 OECD member countries.
4. Levy and Murnane (1992) provide a survey.

computer science discipline furnishes a good example for these dynamics. In response to dramatic technological innovations and subsequent high industry demand, the information systems profession experienced severe shortages of faculty starting in the 1960s. Concurrent with productivity swings, faculty salaries and the excess demand for new faculties declined in the mid 1970s, and recovered in the mid 1980s (Jarvenpaa *et al.* (1991) and Gries and Marsh (1988)).

Theoretical models that consider interaction between endogenous technological change and skills include Stokey (1988) where innovations are the accidental by-product of learning by doing. Chari and Hopenhayn (1991) construct a model of technological diffusion where agents invest in vintage-specific human capital to learn about exogenous technological change. Young (1993) and Grossman and Helpman (1991 Ch. 5.2) endogenize both human capital and technological change. Young assumes homogeneous labour learns serendipitously about privately invented technologies. Since learning arrives as benefit without cost, neither the private incentives for human capital accumulation, nor the costs of absorbing technological change in terms of movements of the relative wage, can be explored. Grossman and Helpman employ a Findlay and Kierzkowski (1983) style education sector that requires no skilled labour. Hence incentives to invest in human capital, in the steady state, depend only on an exogenously specified schooling technology and time preference, which then also fix the relative wage exogenously. Consequently, labour supply effects dominate the comparative statics, which then predict that higher rates of technological change are associated with either constant, or lower relative wages.[5]

Our structure is complementary to the large class of models of endogenous technological change that focus on private incentives to invest in research and on serendipitous learning or fixed human capital. We construct an overlapping-generations model in which private incentives induce agents to invest in education, and where non-rival inventions are the by-product of the education process. To invest in human capital, young agents forgo income as unskilled labour and become "students", who pay "tuition" to enter an education sector. This period's students become next period's stock of skilled labour, who participate in the dissemination of the new technology in either education or production. Investment in human capital requires borrowing against future income to finance the direct (tuition) cost and consumption during time spent in school. We explicitly model the supply and demand for funds in a bond market that is regulated by an endogenous interest rate, which turns out to be a simple expression for the cost-benefit of human capital investment.

We want to think of the education process as a broad set of relationships, ranging from a professor/research assistant relationship in a university setting, to time spent by partners in law firms, doctors in hospitals, and skilled craftsmen to train younger workers. Prescott and Boyd (1987) have termed such relationships "coalitions". In their model young and old agents' productive capabilities (in education and manufacturing) do not depend on the individual's human capital investment but on the coalition's jointly and cumulatively determined knowledge. Two assumptions are crucial for our education sector. First, it imposes a resource cost to society: skilled labour must be withdrawn from production to educate students. Second, the education process produces research output as a by-product. In the most formal setting of higher education, universities, 70% of research is commonly classified as "advancement of knowledge", or unpatented basic research.[6] Jaffe (1989) documents the significant spillovers effects of academic research on commercial

5. Higher rates technological change and lower relative wages are the result of an exogenous increase in the productivity of the schooling technology.

6. National Science Board (1987, Appendix Table 4-7).

innovation, while Trajtenberg *et al.* (1992) show that academic research is more basic and less frequently patented.

In Section II we introduce the assumptions and the setup of the model. In Section III we characterize the general equilibrium, perfect-foresight dynamics and balanced growth. Section IV examines the comparative statics and Section V concludes.

II. THE ECONOMY

Consider an overlapping-generations model with agents who live for two periods. The supply side has a 3×3 structure. Two production sectors manufacture one homogeneous consumption good, but differ in their technological sophistication and skill-intensity. The education sector offers young agents the opportunity to accumulate human capital, while generating ever new technological vintages.

In each period, a new generation of agents enters the economy with a zero endowment of human capital. Young agents must decide whether to accumulate human capital and enter the education sector as students, S_t, or to work in production as unskilled labour, U_t. This period's students become next period's stock of skilled workers, who choose to spend their time in either the education sector, as "teachers" P_{t+1}, or in production, as "engineers", E_{t+1}. For simplicity, unskilled labour retires when old.

Unskilled workers consume part of their first-period income and save the remainder to finance their second-period retirement consumption. In contrast, students do not receive income while in school and borrow against their future income as skilled labour to finance both first-period consumption and the cost of human capital accumulation. A bond market regulates the savings of unskilled labour and the borrowing of students at an endogenous interest rate r_t.

*II.*1. *Production*

At time t, the education sector employs teachers, P_t, students, S_t, and the cutting edge, non-rival technological vintage, v_t (the technology invented in t), to produce a new, non-rival technological vintage, v_{t+1}. Specifically, young agents enter the education sector together with teachers at an exogenously specified student–teacher ratio, γ,[7]

$$v_{t+1} - v_t = \mu v_t \min[\gamma P_t, S_t], \qquad \gamma > 1, \mu > 0, \tag{1}$$

where μ is a productivity parameter. Equation (1) can be decomposed into two alternative, even simpler, representations $v_{t+1} - v_t = v_t \mu \gamma P_t$, (1a) and $\gamma P_t = S_t$ (1b). The decomposition highlights that the education sector is an amalgam of the standard research sector (1a) in models that follow Romer (1990), and the simplest formulation of the education process (1b), first introduced by Bhagwati and Srinivasan (1977). We prefer (1) to the decomposition, since it better captures the notion that students acquire skills by accumulating knowledge about the cutting-edge technology that is being invented.[8]

7. Alternatively, one could follow Shell (1966) by specifying that a research manager, who maximizes output, imposes γ.

8. If we allow for a number of education sectors to generate new technologies, equation (1) can be interpreted as a random sequence of innovations that is produced in the economy. Tirole (1988) and Aghion and Howitt (1992) show that we can re-interpret (1) so that the Poisson arrival rate of innovation in the economy at any instant is simply $\mu \Upsilon[S_t, P_t]$. μ would then be the arrival parameter and Υ could be any constant returns production function, in our case it is the Leontief.

As mentioned above, students, who enter the education sector to become skilled labour next period, pay tuition to learn about new technologies. The direct (tuition) cost per student, z_t, then just equals the teacher–student ratio times the teachers' wage, w_t^P/γ. Thus, private incentives to invest in education finance the teachers' wage bill and generate serendipitous technological change. This drives a wedge between the private and social benefits to human capital accumulation. Note also that models following Romer (1986) and Lucas (1988) specify an *ad hoc* externality to human capital investment. The structure of our education process offers a possible mechanism how such an externality might be generated.[9]

The new technological vintages that are invented in the education sector are assumed to be non-rival. However, the requirement for their future use in either production or research is that skilled labour with knowledge of that particular technology must be employed to absorb or improve upon the vintage. Therefore, while a higher rate of technological change shifts the production possibilities, it simultaneously drains the pool of skilled labour available to the education sector and thus retards future technological change. Note also that S_t represents the endogenous share of each generation that obtains schooling; this share will be constant in the steady state. Since each generation of students learns about a more productive vintage of technology, the *quality* of the stock of skilled labour also increases endogenously.

The High-Tech sector utilizes the cutting edge technological vintage, v_t, and unskilled labour, U_t^H, who perform routine tasks. In addition, the absorption of a new technology requires the employment of skilled labour, or engineers, E_t, with knowledge of the vintage, who adapt the new technology to the production process,

$$H_t = v_t F[U_t^H, E_t], \tag{2}$$

where $F[\cdot]$ is an ordinary point-in-time, linear homogeneous, monotonic, production function. Following Nelson and Phelps (1966), we specify that the absorption of new technology in the High-Tech sector is skill-intensive, in that it requires skilled labour to adapt the technology to the production process. However, once a technology has been absorbed, production requires only unskilled labour.[10] Thus, the Low-Tech production sector utilizes only old technology, v_{t-1} (absorbed in the previous period), and unskilled labour, U_t^L, to perform the now routine tasks,

$$L_t = v_{t-1}\delta U_t^L; \qquad \delta > 0, \tag{3}$$

where δ is the productivity parameter of unskilled labour.[11] The Low-Tech sector thus acts as a "reservoir" for unskilled labour, one which expands if the skilled labour supply available for absorption decreases.

Whenever a new technology is introduced into the High-Tech sector, the recently absorbed technology can now be used in the Low-Tech sector, and the oldest production method is no longer profitable and is thus discarded.[12] In a sense the production side

9. Existence and the appropriate choice of a social welfare function along with a Pareto-improving policy, has been addressed in Eicher (1994).

10. When the first computers were invented, operating systems were tedious and firms that wanted to employ computer technology had to hire electrical engineers from the research sector that developed computers. Today, operating systems are almost foolproof and even programming can be performed by high school students.

11. One interpretation of δ might be that it reflects the "dexterity" of the unskilled.

12. From here on, we assume incomplete specialization. As in all two sector models, the shutdown condition depends on the elasticity of substitution in production and on the resource constraints. Our assumption of $\gamma > 1$ rules out the shut down of the High-Tech sector along balanced growth paths, and $f'[0] = \infty$ is a sufficient condition to insure continued adoption of new technologies in the High-Tech sector along transition paths. If the Low-Tech sector shuts down because of the resource constraint, the model loses its absorption effect and will be entirely driven by labour supply effects.

represents the notion of a product cycle (Grossman and Helpman (1991)), where ongoing innovation and imitation occurs in the same industry and in our case, also in the same country.

Production of the consumption good takes place in perfectly competitive sectors. Rewriting H_t in intensive form, such that $F[U_t^H, E_t]=f[U_t^H/E_t]E_t$, profit maximization yields the standard first-order conditions

$$w_t^E = v_t\left(f\left[\frac{U_t^H}{E_t}\right] - f'\left[\frac{U_t^H}{E_t}\right]\frac{U_t^H}{E_t}\right), \tag{4}$$

$$w_t^{UH} = v_t f'\left[\frac{U_t^H}{E_t}\right], \tag{5}$$

$$w_t^{UL} = \delta v_{t-1}. \tag{6}$$

The factor market equilibrium requires

$$w_t^P = w_t^E, \tag{7}$$

$$w_t^{UL} = w_t^{UH}. \tag{8}$$

Equation (7) says that the wage of a skilled worker as an engineer in the High-Tech sector or as a teacher in education equals her marginal product in the High-Tech sector; simply stated, students, who collectively "buy the teachers' time", must pay the teachers' opportunity cost.[13] Equation (8) states that the marginal products of the unskilled in both sectors must be equalized.

Given linear homogeneity of $F[\cdot]$, the relative wage in the High-Tech sector depends only on the relative factor prices

$$\frac{w_t^E}{w_t^{UH}} = \zeta\left[\frac{U_t^H}{E_t}\right], \qquad \zeta' > 0. \tag{9}$$

Substituting (5) and (6) into the factor-market equilibrium condition (8) yields an expression for relative factor demand in the High-Tech sector, $U_t^H/E_t = \lambda[v_t/v_{t-1}]$, where $\lambda[\cdot] \equiv f'^{-1}[\cdot]$ which implies $\lambda[\cdot] > 0$ and $\lambda'[\cdot] < 0$. After substituting for the rate of technological change in the education sector, the relative wage of skilled labour can now be expressed as a function of past investment in human capital,

$$\frac{w_t^E}{w_t^U} = g\left[\frac{\delta}{1+\mu S_{t-1}}\right], \qquad g'[\cdot] < 0 \tag{10}$$

where $g[\cdot]$ is the composite of $\zeta[\cdot]$ and $\lambda[\cdot]$. Equation (10) highlights the forceful implications of the differing factor intensities and technological sophistication in the two production sectors. It is by no means obvious from that assumption that more human capital investment must raise the relative wage of skilled labour, as (10) implies. From an intertemporal perspective, higher investment in human capital in $t-1$ increases the number of teachers, P_{t-1}, and generates more rapid technological change that must be absorbed in t. The absorption of an increased rate of technological change, creates skill-biased labour demand, which in turn increases the relative wage. Thus the production structure yields a positive, interactive relationship between human capital investment at time t and

13. Again, this is a standard assumption; see, for example, Bhagwati and Srinivasan (1977).

the relative wage at $t+1$, or alternatively, between technological change at t and skilled labour demand at $t+1$.

The thus-modelled advances in technology accord with the empirical findings cited above, which document significant interactions and complementarities between human capital accumulation and technological change. In addition, the economy experiences dynamic benefits to human capital accumulation and technological change, as an incremental increase in human capital investment raises the subsequent level of technology available for future research, and thus creates cumulative productivity effects for future generations. A higher rate of human capital investment thus enhances an economy's ability to obtain more from its physical endowments, an effect that Scherer (1992) labels a "virtuous spiral". Equivalently, a failure to maintain the pace of human capital accumulation relative to competing economies undermines the domestic economy's capability to invent and absorb future advances in technology, inducing a vicious cycle of industrial stagnation.[14]

II.2. Labour constraints

The generation's growth rate is set to zero, and its size is normalized to unity. Then the labour constraints at time t are simply

$$U_t = U_t^H + U_t^L, \tag{11}$$

$$1 = S_t + U_t, \tag{12}$$

$$S_{t-1} = P_t + E_t. \tag{13}$$

II.3 Utility optimization

The demand side closes the model and determines the supply of students and unskilled labour, S_t and U_t; the allocation of skilled labour between the education and absorption processes, P_t and E_t; and the rates of technological change and economic growth, $\hat{v}$, ϕ. Individuals share identical tastes, and those born at time t derive utility[15]

$$W^j = \ln c_t + \beta \ln c_{t+1}, \qquad \beta > 0, \tag{14}$$

where j represents the respective career paths of skilled or unskilled, and c_t represents *per capita* consumption in t. Each unskilled worker receives a wage, w_t^U, early in life and saves, x_t, for retirement. Each student borrows, b_t, against future income, w_{t+1}^E, to finance tuition, z_t, and first-period consumption. Thus, the respective budget constraints of unskilled and skilled are,

$$c_t^U = w_t^U - x_t, \tag{15}$$

$$c_{t+1}^U = x_t(1 + r_t). \tag{15'}$$

$$c_t^S = b_t - z_t, \tag{16}$$

$$c_{t+1}^E = w_{t+1}^E - b_t(1 + r_t). \tag{16'}$$

14. Such a vicious cycle is documented for the case of Britain in Elbaum and Lazonick (1986).

15. Using the equality between total consumption and total output, it can easily be shown that any CARRA utility would yield qualitatively similar results along balanced growth paths.

The first-order conditions from the respective maximization problems provide *per capita* borrowing and saving,

$$x_t = \theta w_t^U, \tag{17}$$

$$b_t = \theta(z_t + w_{t+1}^E/(\beta(1+r_t))), \tag{18}$$

where $\theta \equiv \beta/(1+\beta)$ denotes the marginal propensity to save. Since skilled workers receive a wage when old, their optimal borrowing increases in their future discounted income $(w_{t+1}^E/\beta(1+r_t))$. More patience, or an increase in β, depresses students' demand for funds, since more consumption is deferred into the future. Higher tuition, z_t, decreases the present-period consumption possibility and induces students to transfer more income from the future to the present through increased borrowing.

II.4. The bond market

Saving and lending takes place in a bond market regulated by an endogenous interest rate. The bond market-clearing condition requires that total borrowing equals total saving,

$$S_t b_t = U_t x_t. \tag{19}$$

The *per capita* supply and demand of credit, in conjunction with the number of borrowers and lenders, then determines the interest rate. Substituting *per capita* savings and borrowing ((17) and (18)) into the bond market yields the bond market clearing interest rate, contingent on the number of students and unskilled,

$$(1+r_t) = \frac{w_{t+1}^E}{\beta\left(\frac{U_t}{S_t} w_t^U - z_t\right)}. \tag{20}$$

II.5. Career arbitrage

To close the model, the determination of the equilibrium interest rate, and thus the stock of students, requires one more condition. Since the young enter the economy as identical agents, they must be indifferent between either career path, or,

$$W^U = W^S. \tag{21}$$

Since agents share identical utility functions and face identical intertemporal transformation possibilities (21) implies $c_t^U = c_t^S$, and $c_{t+1}^U = c_{t+1}^E$. Equation (21) can be modified to reflect a credit constraint, or an ability density function. Such departures from the identical agent assumption do not alter the implications of the model.

Career arbitrage, bond market clearing and utility optimization then provide investment in human capital, S_t, and the stock of human capital allocated to the education sector, P_t.

$$S_t = \frac{\theta}{\frac{w_t^E}{\gamma w_t^U} + 1}, \tag{22}$$

$$P_t = \frac{\theta}{\frac{w_t^E}{w_t^U} + \gamma}. \tag{23}$$

The stock of students depends positively on the marginal propensity to save, θ, and negatively on a measure of the costs of human capital investment: the cost of tuition w_t^E/γ, times an index for the cost of funds, $1/w_t^U$.[16] Equation (22) also establishes a relation to the previous endogenous human capital literature. If we assume with Grossman and Helpman (1991, Ch. 5.2) that incentives to accumulate human capital are independent of the cost of absorbing technology, the stock of students in (22) would be determined solely by the marginal propensity to save, θ. That is, we can replicate the Grossman and Helpman structure by "turning off" the absorption effect, if we eliminate the direct (tuition) cost to students. As in Grossman and Helpman, the relative wage would then be fixed by the time preferences.

Note the importance of including both the direct and indirect cost of education. While the wage of skilled labour at time t may be high, students in that period care about their *future* wage as skilled labour (which influences the interest rate). A high wage of skilled labour at t represents, however, a high cost of human capital accumulation to students in that period. The benefits of human capital investment are directly tied to technological change, since the wage of skilled labour at time $t+1$ is influenced by the rate of technological change that is invented at t, which must be absorbed at $t+1$.

Having obtained the stock of students, we derive the equilibrium interest rate

$$(1+r_t)=\frac{w_{t+1}^E}{w_t^U+w_t^E/\gamma}. \tag{20'}$$

Given lifetime equalization, the interest rate is simply the benefit/cost (direct and indirect) ratio of investing in human capital. The bond market, in which the interest rate is determined, is special and deserves a closer look. Generally, models with zero growth, homogeneous agents and capital as both a productive input and as an asset to carry income forward, imply that higher savings depress the interest rate (or the marginal product of capital). Here, the share of each generation that decides to borrow and invest in human capital is not only the vehicle to carry income into the future, but students also hire skilled labour into the education sector to create technological change, which in turn increases future production possibilities and growth. However, higher investment in human capital creates a higher rate of technological change, whose cost of absorption in the next period raises the relative wage. As students expect the relative wage to rise tomorrow, their borrowing demand rises, which increases the interest rate, (20'). Simply stated, as higher economic growth raises the marginal rate of substitution, it must also raise the marginal rate of transformation.

III. GENERAL EQUILIBRIUM, PERFECT FORESIGHT DYNAMICS AND BALANCED GROWTH

At any point in time, the relative wage, conditional on past human capital investment, is determined by the supply side, while human capital investment, conditional on the relative wage is determined by the demand side and bond market clearing. Combining the key

16. Note that the opportunity cost is not insignificant. Equation (22) can also be written as $S_t=\theta w_t^U/(w_t^E/\gamma+w_t^U)$, which clearly highlights the positive effect of increased lending, θw_t^U, and the negative influence of an increased (direct and indirect) cost, $(w_t^E/\gamma+w_t^U)$, on human capital investment.

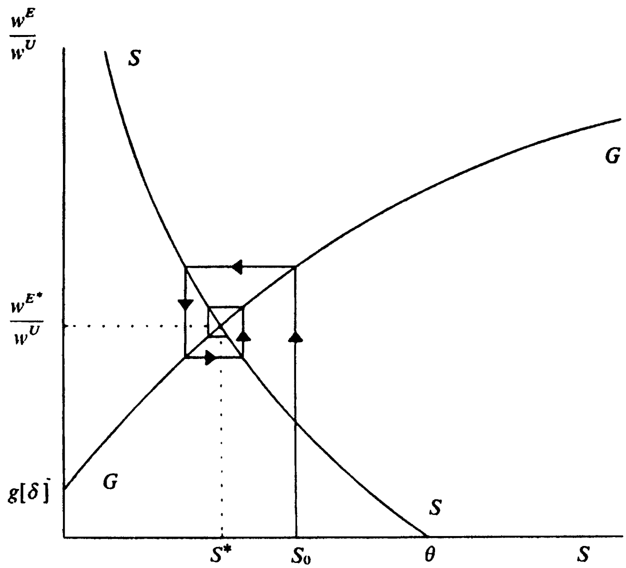

FIGURE 2

Transition dynamics and equilibrium

Note: Oscillatory transition dynamics are the result of interaction between technological change and human capital accumulation. The link between the two is the relative wage, which reflects both the cost of absorbing technology into production and the incentives to accumulate human capital.

equilibrium conditions, equations (22) and (10), yields the difference equation that characterizes the general equilibrium,

$$S_t = \frac{\theta}{\gamma^{-1} g\left[\dfrac{\delta}{1+\mu S_{t-1}}\right]+1}. \tag{24}$$

Equation (24) determines the amount of human capital investment at t as a function of the existing stock of skilled labour: $S_t = \xi[S_{t-1}]$, where ξ is a strictly decreasing function.

The functional relationship ξ between human capital investment in two successive periods, characterized in Figure 2, highlights the intertemporal and intratemporal interaction between technological change and human capital accumulation. The SS$[S_t]$ schedule (22), represents the "marginal cost of human capital investment", which is strictly decreasing since SS$[S_t]\to\infty$ as $S_t\to 0$. The higher the wage of skilled labour in period t, w_t^E, the higher the cost of schooling, while an increase in the wage of unskilled labour, w_t^U, raises the supply of funds and thus decreases the cost of borrowing. The GG$[S_{t-1}]$ schedule (10) is strictly decreasing and represents "marginal benefit of human capital investment", as it relates investment in $t-1$ to the relative wage in t, when new technology must be absorbed. More explicitly, higher human capital investment in $t-1$ increases the number of skilled workers hired into the education sector, which raises the rate of technological change. In t, Hicks-neutral technological change biased to the skill-intensive High-Tech sector then raises the cost of absorbing technological change.

GG and SS schedules thus summarize two distinct feedback effects that generate oscillatory dynamics. For example, higher than steady-state rates of technological change have two costly consequences. First, a higher relative wage draws human capital into the High-Tech sector and drains teachers from the research sector. Second, the relative cost of becoming a student increases since hiring teachers has become more expensive. Thus, the number of students falls, which, together with the reduced amount of teachers, retards the output of technology in the education sector. This result is crucial as it extends the original insight of earlier models of endogenous technological change, which hold that advances in technology generate only a resource cost, i.e., reduction of inputs available for manufacturing. Our model adds the additional insight that the very stock of human capital, the crucial R&D and production input, is also altered, since the cost of human capital accumulation is affected by the rate of technological change.

We can now define a perfect foresight equilibrium as a sequence $\{S_t\}_0^\infty$ satisfying (24) for all $t \geqq 0$. In Figure 2 the sequence $\{S_0, S_1, S_2, \dots\}$ generates a counterclockwise spiral that constitutes a perfect-foresight equilibrium. A stationary equilibrium corresponds to a perfect-foresight equilibrium with S_t constant, defined as the solution to $S^* = \xi[S^*]$. There exists a unique, stable stationary equilibrium.[17] As Figure 2 shows, S^* is positive and defined by

$$S^* = \frac{\theta}{\gamma^{-1} g\left[\dfrac{\delta}{1+\mu S^*}\right] + 1}. \tag{25}$$

Another equilibrium may exist. A two-cycle is a pair (S_0, S_1) such that $S_0 = \xi[S_1]$ and $S_1 = \xi[S_0]$, which then defines a perfect-foresight equilibrium of period two. In a two-cycle, high investment in human capital in odd intervals generates excessive absorption costs; the corresponding rise in the direct cost of education strongly discourages human capital investment in even intervals. In contrast, the low investment in human capital in even intervals generates such a slow rate of technological change and so little demand for skilled labour to absorb technology during odd intervals that the cost of education is again reduced.[18]

As mentioned in the introduction, oscillatory dynamics are not new to the empirical human capital literature. Until the late 1980's, explanations of relative wage fluctuations centered largely on cohort effects and labour supply factors (Freeman (1976)). When Murphy and Welch (1992) and Katz and Murphy (1992) distinguished meticulously between supply and demand shifts, the effect of technological change on the inverse fluctuations of supply and demand for skilled labour become apparent. Note that our model explains these "demand driven" oscillations with a new feature: the absorption effect. That is, bursts in technology generate not only the costly side effects of increased relative demand and wages of skilled labour, but resources are also being drained from the education sector, which raises the cost of future human capital investment. This pattern is

17. Since $dS_t/dS_{t-1} = \theta\mu\delta g'[\cdot]/[\gamma(1+\mu S_{t-1})^2(\gamma^{-1} g[\cdot]+1)^2] < 0$, we know the system oscillates. A (strong) sufficient condition for stability is then that the elasticity of the relative wage with respect to past changes in the rate of technological change (or human capital investment) times μ (the productivity of labour in research) must not exceed unity. Or, $\mu\sigma_{w_t^E/w_t^U : v_t/v_{t-1}} \leqq 1$, where

$$\sigma_{w_t^E/w_t^U : v_t/v_{t-1}} = \frac{dw_t^E/w_t^U}{dv_t/v_{t-1}} \frac{v_t/v_{t-1}}{w_t^E/w_t^U} = -\frac{\delta g'[\cdot]}{(1+\mu S_{t-1})g[\cdot]} > 0,$$

18. The condition for the two-cycle equilibrium can easily be read off the equations provided for the stability analysis. It depends again on the elasticity of the relative wage with respect to changes in technology. A no-growth trap has been ruled out by $\beta > 0$. If we allowed human capital investment to cease, no technology would be invented, the High-Tech sector would collapse and the economy would simply replicate itself with the Low Tech sector as the sole sector of production.

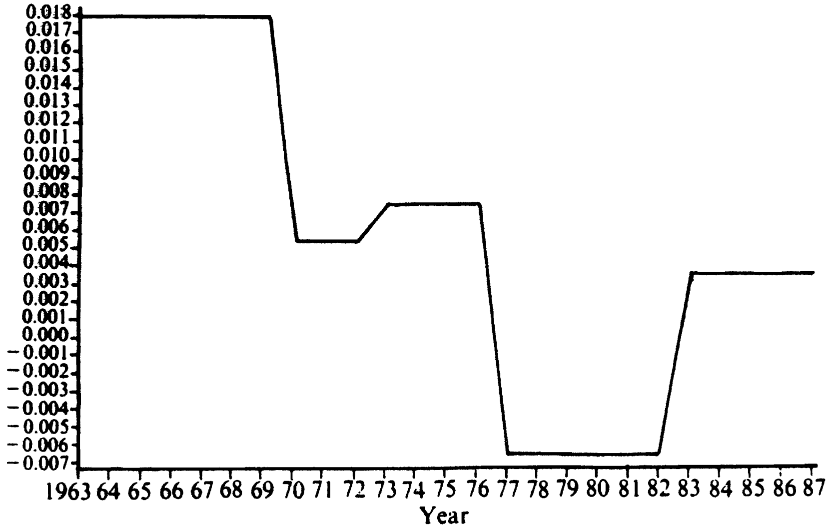

FIGURE 3

Total factor productivity growth

Source: Jorgenson and Fraumenti (1987), updated.

reflected in the data for U.S. cost of education and faculty salary data. Tuition costs exploded in the 1980's, while faculty salaries mirror the relative wage movements in Figure 1 (U.S. Department of Education (1993)).

The mechanics of the model imply that relative wage and supply movements are driven by skill-biased labour demand generated by technological change. It is thus reasonable to inquire whether the data provide evidence that corresponding swings "technological change" can be observed. Since any proxy for "technology" is imperfect, we examine two measures: total factor productivity (TFP), and research outlays. TFP is highly correlated with output growth, and following seven years of decline, TFP rebounded to over 3% in 1983 and 1984. Figure 3 shows the Jorgenson TFP measure, which is more accurate for our purposes.[19] It shows convincingly that the 1980's saw a significant rise in TFP, which might be interpreted as the cause for the subsequent skill-biased labour demand. However, rather than measuring technology by means of the Solow residual, for our purposes research outlays might be another worthwhile proxy to examine. Figure 4 shows that the cyclical behaviour of R&D per worker corresponds exceedingly well with the relative wage and supply fluctuations we observed in Figure 1.

To document how fluctuations in technological change affect the relative wage, the empirical literature has examined various technology proxies. Krueger (1993) uses computerization and estimates that its extraordinary growth in the 1980's increased the wage differential by about 15%. Bartel and Lichtenberg (1987) use the age of capital as a proxy to show that industries with newer capital have had higher skill-biased labour demand in the 1980's. Mincer (1991, 1993) uses R&D intensity as a proxy, which exhibits the same fluctuations as our Figure 3.

19. Jorgenson's measures contain more detailed adjustments of labour inputs for quality components, such as education. The productivity growth residuals are thus largely purged of human capital effects. Also, the systematic error, due to business cycles is adjusted for by using moving averages.

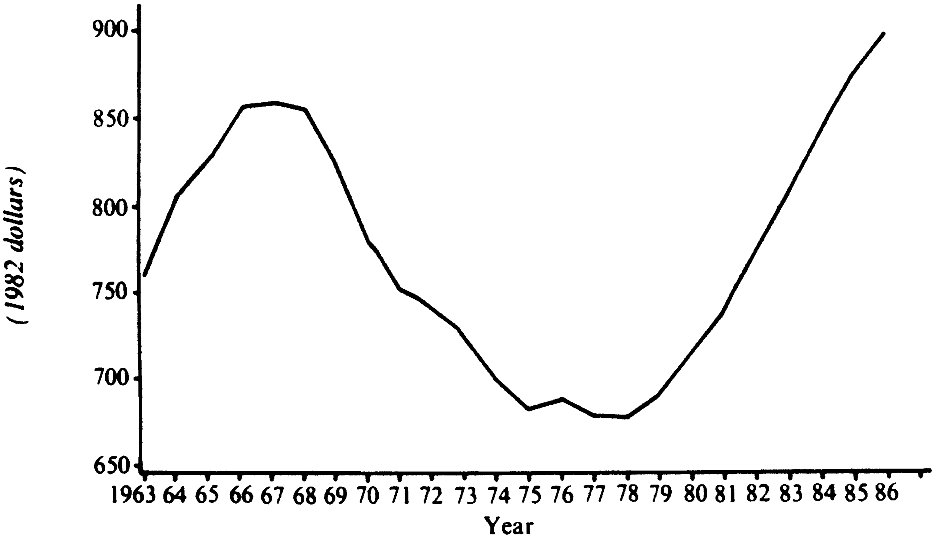

FIGURE 4
R&D expenditures per worker
Source: BLS (1989).

IV. DETERMINANTS OF LONG-RUN GROWTH

The rest of the paper focuses on stationary equilibria. The model generates an endogenous rate of long-run growth. Logarithmic differentiation of steady-state income, $Y^* = w^{U^*}U^* + w^{E^*}E^*$ (which can easily be shown to equal aggregate steady-state consumption C^*), yields

$$\phi = \hat{Y}^* = \frac{(\hat{w}^{U^*} + \hat{U}^*)w^{U^*}U^* + (\hat{w}^{E^*} + \hat{E}^*)w^{E^*}E^*}{Y^*} = \hat{C}^*. \tag{26}$$

But in the steady state $\hat{U}^* = \hat{E}^* = 0$, and $\hat{w}^{E^*} = \hat{w}^{U^*} = \hat{v}^*$. Thus (26) yields the long-run growth rate

$$\phi = \hat{Y}^* = \hat{C}^* = \hat{v}^* = \mu\gamma P^* = \mu S^*. \tag{26'}$$

At first sight, the growth rate in (26′) seems identical to the one derived in Romer (1990), who assumes fixed human capital, private incentives to invest in rival technology, and monopolistic competition. The similarity stems from the fact that the linearity of output growth in both models has its origin in the production of new technology. Yet, in clear contrast to Romer's fixed human capital, equation (25) provides a crucial explanation (as discussed above in Figure 2) of the determinants of the stock of skilled labour, S^*. This added insight is significant. Romer (and most other models of endogenous technological change) examines the effects of an exogenous increase in skilled labour. Our model implies, however, that the skilled labour supply cannot be varied at will, but is inextricably tied to the rate of technological change. This explains the empirical inconsistency in Romer's comparative statics, where higher rates of a larger stock of skilled labour raises the rate of technological change but depresses the relative wage. We will show below that a smaller stock of skilled labour can be associated with higher rates of technological change, and that higher relative wages can be associated with lower relative supply of skilled labour.

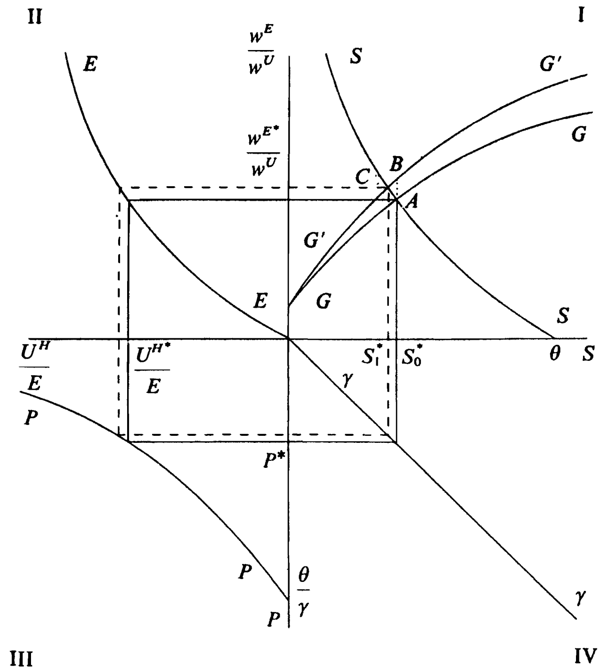

FIGURE 5

Note: Higher productivity of workers in research lowers the skilled labour supply, but raises the relative wage, and the rates of technological change and growth.

Grossman and Helpman (1991, Ch. 5.2) allow human capital accumulation, but abstract from the resource and direct cost of education. Thus, no parametric changes (other than the productivity of time spent in school and the rate of time preference) alter the steady-state relative wage. As a consequence, their growth rate is either independent, or varies inversely with the relative wage (if the productivity of time spent in school is increased exogenously), while the changes in the stock of skilled labour depend on the assumed functional forms. The next section contrasts the implications of this model, as expressed in equations (25) and (26′), with those of the previous literature.

VI.1. Human capital and technological change in stationary equilibrium

The rest of the paper focusses on stationary equilibria. We now analyze how the parameters of the model influence the relative demand, supply and wage of skilled labour and the long-run growth rate. The four-quadrant diagram in Figure 5 facilitates the analysis as it represents the solution to the four key variables of the model: S_t, P_t, w_t^E/w_t^U, U_t^H/E_t. Quadrant I shows the interaction between the supply and demand for skilled labour, which has been examined above in our discussion of Figure 2. Quadrant II shows the relation between the cost of absorption and relative factor demand in the High-Tech sector. The EE schedule (10) relates the relative wage to the ratio of factor inputs required to absorb the new technological vintage into the High-Tech sector. Quadrant III shows the relation between research and absorption. The PP schedule (23) relates the stock of existing human capital in the education sector, P_t, to the ratio of factor inputs in the High-Tech sector (10). Quadrant III shows that the more pressing the need to absorb new technologies, the higher the relative wage paid in production, and the smaller the number of teachers available for research. More skilled labour is drawn into the High-Tech sector, despite the fact that the factor input ratio rises. Finally, the $\gamma\gamma$ schedule in quadrant IV, relates investment in human capital to the number of teachers financed in the education sector.

Proposition 1. *An increase in effectiveness of labour in research, μ, decreases the relative supply of skilled labour, but increases the relative demand for skilled labour, the relative wage, w_t^E/w_t^U, the rate of technological change, and long-run growth, ϕ.*

The first interesting implication of the model is that bursts in technological change which originate in the education sector increase the long-run rate of technological change, but lower the relative supply of skilled labour, *despite* increased skill-biased labour demand. Two effects occur consecutively. First, a higher rate of technological change generates greater Hicks-neutral technological change in production, which is biased to the skill-intensive High-Tech sector. The relative wage, (10), rises with the increased the cost of absorption, which is represented by an upward shift in the GG schedule (A to B in Figure 5).

Secondly, recall that the absorption cost is the crucial link between technological change and the incentives to accumulate human capital. Absorption comes at the "expense" of skill-biased labour demand, which drains skilled labour from research and raises the cost of education. Despite a possible high social payoff to investment in technological change private investment in human capital declines since innovations are not privately appropriate. Implicit differentiation of (25) confirms that an increase in μ has a negative impact on S^* in the long-run. Human capital investment, S^*, thus declines as the economy moves from the impact equilibrium (B) to the new steady state (C).

Since the initially high rate of technological change cannot be sustained with fewer students, the rate of technological change decelerates from its initial burst. Thus, the move from B to C is accompanied by progressively lower costs of absorption, and thus a lower relative wage. With μ rising and S falling, the effect on the growth rate seems ambiguous at first. Totally differentiating the growth rate, $\phi=\mu S^*$, with respect to μ yields

$$\frac{\partial\phi}{\partial\mu}=\mu\frac{\partial S^*}{\partial\mu}+S^*>0 \quad \text{if } 1>-\frac{\mu}{S^*}\frac{\partial S^*}{\partial\mu}, \tag{27}$$

which clarifies the two effects of an increase in μ on the long-run growth rate. Each student (and teacher) in the education sector produces more technological change, but the smaller stock of students depresses the rate of technological change. The aggregate effect can only be positive if the absorption cost (which causes the decline in S^*) does not outweigh the increase in technological change generated by an increase in the productivity agents in research. From (25) it can easily be shown that ϕ increases as long as stability is assured. A higher rate of growth implies a higher equilibrium relative wage compared to the previous steady state (10).

The adjustment in the bond market also exhibits interesting dynamics. As both future income and cost of tuition rise, the per student borrowing demand increases sharply to smooth consumption between periods (18). At the same time, however, the student–unskilled worker ratio falls, resulting in an increase in the number of lenders and in a decrease in the number of borrowers. The aggregate effect on the interest rate must be positive, as it represents the marginal rate of transformation, which must equal the intertemporal marginal rate of substitution that rises with the rate of growth.

The implications of Proposition 1 allow us to draw a parallel to the real world puzzle, where higher U.S. economic growth in the 1980's (compared to the 1970's), higher relative demand and wages for skilled labour, has been associated with a *lower* relative supply of the same. The above structure relies exactly on the observed characteristics of the 1980's, a computer revolution, a premium paid to skilled labour with the ability to adapt the technology to the production process (Krueger (1993)), and a sharp rise in the cost of education (Mincer (1994)).

Proposition 2. *An increase in the basic skills (productivity or dexterity) of unskilled labour, δ, increases the relative supply of skilled labour, decreases the relative demand for skilled labour and the relative wage, w_t^E/w_t^U, while increasing the rate of technological change and long-run growth, ϕ.*

Proposition 2 is crucial since it shows that higher growth and technological change does not have to come at the expense of increased income inequality. It highlights that raising the level of basic skills serves as an engine for growth as it allows more investment in human capital and higher rates of technological change.

On impact, higher basic skills increase the wage of unskilled labour, w_t^U, which corresponds to a decline in the relative wage. The GG schedule (10) shifts down and, *ceteris paribus*, the cost of funds falls, since a higher income of unskilled translates into higher savings (17) to create excess supply in the bond market. As the interest rate (20) falls, student loans become cheaper and the incentive to invest in education increase.

The subsequent increase in human capital investment increases the rates of technological change and growth. Again, a higher rate of technological change causes a Hicks-neutral shift in production, biased to the High-Tech sector. Skill-biased labour demand then returns upward pressure on the relative wage, thus raising the cost of absorption until the new equilibrium is reached.

The fall in the relative wage (due to higher productivity of the unskilled) outweighs its subsequent rise (due to skill-biased labour demand and higher absorption cost). This implies that both S^* and the rate of growth, ϕ, must increase (which can be confirmed by implicitly differentiating S^* with respect to δ). By the same reasoning employed in Proposition 1, an increase in the growth rate must lead to a rise in the interest rate.

Proposition 3. *The relative supply, demand and wage of skilled labour, as well as the rates of technological change $\hat{v}$, and long-run grwoth, ϕ, increase with: (a) an increase in the student–teacher ratio, γ; (b) an increase in the marginal propensity to save θ; or (c) an increase in the size of the generation.*

Having discussed the mechanics of adjustment in Propositions 1 and 2, Proposition 3 is intuitive: (a) An increase in the student–teacher ratio lowers the per student tuition cost, w_t^E/γ, and requires less borrowing per student. The $\gamma\gamma$ ray in quadrant IV shifts by $\Delta\gamma$, while the SS schedule rotates to the right. In addition, per student education now requires the withdrawal of fewer teachers per student from production (from (24) the PP curve shifts in). All effects combine to increase long-run human capital investment, relative wage, technological change and growth. (b) A decrease in the discount rate, β, or an increase in the marginal propensity to save, θ, increases the agents' patience to consume or earn income when old. This increases the savings of unskilled (17) and investment in human capital (22), to raise the marginal benefit and to lower the marginal cost of human capital investment.

(c) An increase in the population size raises the stock of students, the ratio of skilled to unskilled, and the rates of technological change and long-run growth.[20] The model's implications concerning the market size are thus identical to those of other endogenous growth models, which carry the uncomfortable implications that pure size of the labour force matter. Qualitatively, the implication differs, however, from growth models such as Grossman and Helpman (1991) or Young (1993), where market size matters because of market structure or economies of scale. Here a larger economy provides more funds (in absolute terms) to increase its stock of skilled labour, which subsequently generates the (free) benefit of technological change.

V. CONCLUSION

We have presented a model in which the rate of economic growth and movements in the relative wage are sensitive to the interaction between accumulation of human capital and absorption of new technology. From a theoretical perspective, the novel feature of the model is that both the direct and the indirect costs of education, as well as the resources required for education and absorption, are examined explicitly. The consideration of this wide range of costs involved in the growth process exposes an *absorption effect* as the crucial link between the rate of technological change and relative supply, demand and wage of skilled labour. Our analysis of comparative steady-states and balanced growth paths indicates that the "missing link" between technological change and relative wage and supply of skilled labour in the previous endogenous growth literature is exactly the absorption effect, which now allows for inverse movements in the relative wage and supply of skilled labour in response to bursts in technological change. The model thus provides a theoretical foundation for recent empirical findings of positive links between technological change and the relative wage on the one hand, and long-term inverse fluctuations in the relative supply and wage of skilled labour on the other.

One interesting extension of the model would be to explore the effects of private incentives to invest in R&D. One possibility is to depart from the perfectly competitive market structure and allow firms to invest in R&D, to purchase it from the education sector. We conjecture that this extension would only increase the teachers wage fund while none of the qualitative results change. Another possibility is to assign property rights to inventions in the education sector. If students or firms must purchase inventions from teachers, we conjecture that the absorption effect may be muted.

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20. Proof: Relaxing the assumption that population is normalized to unity,

$$U_t + S_t = N, \tag{12'}$$

and deriving the growth rate in the same manner as above, we find that the stock of students, the rate of technological change and the rate of growth rate directly proportional to the size of the population.

$$\phi = \mu S^*, \qquad \text{where } S^* = \frac{N\theta}{\gamma^{-1} g\left[\dfrac{\delta}{1+\mu S^*}\right]+1}. \tag{25''}$$

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