The Supply of Skilled Labor and Skill-Biased Technological Progress

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Abstract

Rising inequality in the relative wages of skilled and unskilled labor in the 1980's is often attributed to skill-biased technological progress. This paper presents a model in which the adoption of skill-biased or "unskilled-biased" technologies is endogenous. Conventional wisdom states that an increase in the supply of skilled labor lowers the relative wage of skilled to unskilled labor. In this paper's endogenous growth model, an increase in the supply of skilled labor leads to temporary stagnation in the wages of unskilled workers and an expanding gap between the wages of skilled and unskilled workers. An increase in the supply of skilled labor accelerates skill-biased technological change, and, under plausible conditions, lowers output growth at least temporarily.

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1. Introduction

Skill-biased technological change has played a central role in recent research on increased inequality in the wages of skilled and unskilled workers[2], and on the slowdown in productivity.[3] One characteristic of this literature is the assumption that skill-biased technological change is exogenous. In the literature on rising wage inequality, this exogeneity is reflected in the fact that the attribution of rising inequality to skill-biased technological change basically amounts to assigning the residual, unexplained increase in inequality to skill-biased technology, rather than examining the factors that contribute to the adoption of skill-biased technologies and relating these factors to rising inequality. This paper takes a first step towards consideration of factors contributing to skill-biased technological change by presenting a model in which growth is endogenously driven by two types of technological advance: skill-biased technology, and "unskilled-biased" technology. The model's predictions for the wages of skilled and unskilled workers and output growth following an increase in skilled labor's share of the labor force are broadly consistent with the rising inequality between the wages of skilled and unskilled labor, and the slowdown in output growth, that followed the surge in skilled labor's share of the labor force in the U.S. during the early 1970's.

Before introducing the model, some motivation can be provided by a brief history review. As summarized in Mincer (1995), economic growth leads to an expansion in the skill level of the workforce (education) for many reasons, including greater consumption of education at higher income levels (as education is a normal good) and the demographic transition. However, these increases in skill have not lead to a downward trend in the returns to skill (education). This leads to the basic question posed in Mincer (1993) and elsewhere: What explains the absence of a significant downward long-term trend in the profitability of education, given massive increases in supplies of educated workers? The standard explanation for the lack of a downward trend in the return to skill is that economic growth is

[2] Examples include Bound and Johnson (1992,1995), Katz and Murphy (1992), Juhn et al. (1993), Mincer (1993,1995), the Federal Reserve Bank of New York Symposium containing Bound and Johnson (1995), Krusell et al. (1996), Greenwood (1996), and Greenwood and Yorukoglu (1996).

[3] Examples include Greenwood (1996), Greenwood and Yorukoglu (1996), and Kahn and Lim (1997).

accompanied by an increased demand for skilled labor because of skill-biased technological change. This paper asks if the increase in the skill level of the workforce can act as one cause of skill-biased technological change in an endogenous growth model.

The potential usefulness of this approach is illustrated through consideration of policy responses to increased wage inequality in the U.S. since the early 1980's. The 1980's witnessed a large increase in the wages of skilled labor relative to unskilled labor, resulting in levels of wage inequality between high and low skilled workers in the U.S. higher than at any time in the last 30 years (*Economic Report of the President* (1997)). One popular explanation of this swing in relative wages is that exogenous skill-biased technological progress increased demand for skilled labor in the 1980's, raising skilled wages. One potential policy response to such an increase in the demand for skilled labor would be programs to expand the supply of skilled labor, as an increase in the supply of skilled labor, and the accompanying decrease in the supply of unskilled labor, works to raise unskilled labor's wages and decrease skilled labor's wages. Does this supply and demand story hold in the model with endogenous skill-biased and unskilled-biased technological advance? No.

In the model below, investment in applied R&D is directed towards either skill-biased technology (i.e., technology complementary to skilled labor) or unskilled-biased technology (i.e., technology complementary to unskilled labor). The attractiveness of investing in skill-biased technology depends on the supply of the factor that complements that technology; specifically, a larger number of skilled workers raises the incentives to invest in technology that skilled labor uses. These factors imply that an increased share of skilled labor raises the level of skill-biased technology relative to the level of unskilled-biased technology.[4] In the language of the labor economics literature, an increase in the supply of skilled labor brings about an increase in the demand for skilled labor, through more technological progress appropriate for skilled labor.

Is the idea that the development or adoption of skill or "unskilled"-biased technologies is driven, at least in part, by the skill composition of the workforce reasonable? Casual

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[4] Acemoglu (1996) presents a model in which the structure of jobs (skill-biased or not) is endogenous, and an increase in skilled labor's share of the workforce can also raise skilled labor's wages in his model. Acemoglu's results differ in that labor market imperfections (search frictions) are key, and there is no growth.

observation certainly suggests so. For example, an article in *Ward's Automotive Reports* (1997) indicates that the technology mix in Mexican automotive assembly plants is different from that in U.S. assembly plants to take advantage of lower labor costs in Mexico. These lower labor costs reflect the lower productivity of Mexican workers, which itself reflects (presumably) lower levels of human capital. Hence, the type of automotive plant chosen depends, to an important extent, on the skill composition of the workforce. Presumably the development or adoption of many technologies reflects the supply of factors complementary to the technology; after all, there is no point in developing a capital good which requires such high levels of skill that no workers can use the capital.

Section 2 presents the model, and section 3 discusses the properties of the balanced growth path, paying particular attention to the effects of the skill composition of the workforce on the relative wages of skilled and unskilled workers. Section 4 then discusses the consistency of the model's stylized implications with recent history and the previous literature, concluding that available evidence is at least not inconsistent with the notion that endogenous skill-biases in technological advance play an important role in wage and output growth. Section 5 concludes with suggestions for future research.

2. The Model

Final Goods

The economy consists of both skilled and unskilled labor (L^s and L^u), with the fraction of skilled labor in the total labor force (L) equal to ω (i.e., $L^s = \omega L$, $L^u = (1-\omega)L$). Both types of labor are combined with intermediate goods to produce final goods output. I assume that intermediate goods complement either skilled or unskilled labor, not both. Intermediate goods that complement skilled labor are denoted by X, and intermediate goods that complement unskilled labor are given by Z. Production of final goods output by firm i (Y_i) follows Romer (1990):

$$Y_i = (L_i^s)^{1-a}\sum_{j=1}^{N}(X_{ij})^a + (L_i^u)^{1-a}\sum_{j=1}^{M}(Z_{ij})^a \ , \qquad (1)$$

where $0<a<1$, X_{ij} is the employment of the jth type of "skill-biased" intermediate good, and Z_{ij} is the employment of the jth type of "unskilled-biased" intermediate good.

Several points about the production process deserve highlighting. First, I assume, through the additive form of (1), that production with unskilled labor and "unskilled-biased" intermediate goods is a perfect substitute for production with skilled labor and "skill-biased" intermediate goods. This assumption reflects the idea that there are different ways to produce a good, and that the choice of the mix of production processes is endogenous; for example, the mix of skilled and unskilled labor chosen by a firm facing production opportunities given by (1) will depend on the intermediate good technologies available to complement skilled and unskilled labor (indexed by N and M, respectively). This characterization of the difference between skilled and unskilled labor being related to the variety of intermediate goods, or "production processes", with which the types of labor are compatible seems a reasonable description of skill differences. Of course, the perfect substitutes assumption is extreme, but it is simple enough to allow solution for the rates of skill-biased technological change and the wages paid skilled and unskilled labor. Future work may examine less extreme assumptions, such as a CES production function with a lower elasticity of substitution between the skilled and unskilled production processes. Also, the share parameters in (1) (given by a) are assumed to be equal in order to minimize on notation below; the share parameters of skilled and unskilled labor could differ in (1), and exogenous productivity constants could multiply both the skilled and unskilled components in (1), without affecting any results below.

Another key point regarding (1) regards the intermediate goods specification. Both skilled and unskilled production exhibit diminishing returns to individual factors and constant returns to labor and intermediate goods. Endogenous skill-biased technological change arises through the expansion of N, the variety of intermediate goods available for production with skilled labor. Similarly, expansion of the variety of goods available for production with unskilled labor (M) constitutes unskilled-biased technological change. To see these effects, assume that all skill-augmenting intermediate goods are employed at the same intensity X, and all unskilled-augmenting intermediate goods are employed at intensity Z (as in the equilibrium below). Under these assumptions, output from (1) is given by

$$Y_i = (L_i^s)^{1-a} N X^a + (L_i^u)^{1-b} M Z^b \,, \qquad (2)$$

which demonstrates that production is linear in the varieties of skilled (N) and unskilled (M) intermediate goods. The constant returns to variety imply that expansion of the varieties of intermediate goods allows for endogenous technological progress, as in the well known "AK" model of endogenous growth.[5]

Final goods output produced by different firms is identical, and can be used for consumption C, for the production of intermediate goods X_j and Z_j, and for research and development to expand the varieties of skill-augmenting and unskilled-augmenting intermediate goods, as detailed below. Profit maximization by competitive final goods producer i yields his demand for the jth skilled and unskilled intermediate goods,

$$X_{ij} = L_i^s(a/P_j^s)^{1/(1-a)} , \tag{3}$$

$$Z_{ij} = L_i^u(a/P_j^u)^{1/(1-a)} , \tag{4}$$

where P_j^s and P_j^u are the prices (in terms of final goods) of the jth skill-augmenting and unskilled-augmenting intermediate goods, respectively.

Intermediate Goods

Intermediate goods producers drive growth in final output through the expansion of skill-augmenting intermediate goods and unskilled-augmenting intermediate goods. Development of a new intermediate good is costly. These costs depend both on how advanced the good is (with the most advanced current skill-augmenting good being denoted by N, and M playing the same role for unskilled-augmenting goods), and on the level of current basic research knowledge (denoted by R and discussed below). The fixed cost of developing a skill-augmenting intermediate good indexed by N is $\Gamma^s(N/R)=\delta_1(N/R)^2$ units of the final good, and development of a new unskilled-augmenting intermediate good indexed by M requires $\Gamma^u(M/R)=\delta_2(M/R)^2$ units of the final good. These simple cost functions satisfy $\Gamma(0) = 0$, $\Gamma(\infty) = \infty$, $\Gamma'(.)>0$, and $\Gamma''(.)>0$. These assumptions on the properties of the cost of developing new goods simply indicate that these costs are negligible when basic research is far advanced relative to "applied technologies" (N/R or M/R near 0), are prohibitive when applied technologies are far advanced relative to basic research (N/R or M/R large), and are increasing and convex. To guarantee higher wages for skilled workers, $\delta_2>\delta_1$.

[5] Barro and Sala-i-Martin (1995) provide an introduction to endogenous growth models. My treatment of the expanding varieties of intermediate goods model follows Barro and Sala-i-Martin closely; the primary difference lies in my differentiation between skilled and unskilled labor.

Given the costs of technological advance, firms must receive some profits from development of a new technology in order to make research and development worth the expense. I assume that developers of new intermediate goods receive a perpetual monopoly right to the production and sale of their intermediate goods. Combining this assumption with the assumption that both classes of intermediate goods cost one unit of final good Y to produce (once the fixed costs of development from above are incurred), the present value of the profits from new intermediate goods of both classes are given by

$$V^s(t) = \int_t^\infty (P_j^s - 1)X_j\, e^{-r(v,t)(v-t)}dv \,, \tag{5}$$

$$V^u(t) = \int_t^\infty (P_j^u - 1)Z_j\, e^{-r(v,t)(v-t)}dv \,, \tag{6}$$

where $V^s(t)$ and $V^u(t)$ are the values for new skill and unskilled-augmenting intermediate goods, respectively, X_j and Z_j are the total quantities of intermediate goods j sold at each date (i.e., the sum of the demands of the final goods producers), and r(v,t) is the average interest rate between times t and v. Of course, if the interest rate is constant, r(v,t) simply equals r.

Summing the demands for intermediate goods of both classes (3) and (4) over the final goods producers yields the demand curves in (5) and (6),

$$X_j = L^s(a/P_j^s)^{1/(1-a)} \,,$$

$$Z_j = L^u(a/P_j^u)^{1/(1-a)} \,,$$

where full employment of the inelastically supplied labor inputs is used. The constant elasticity form of these demand curves implies that the profit maximizing prices in (5) and (6) are constant and equal 1/a for both skill and unskilled-augmenting intermediate goods. Under a constant labor supply of each type of labor, these demand curves imply that the demand for each type of intermediate good is constant at $X=L^s(a^2)^{1/(1-a)}$ and $Z=L^u(a^2)^{1/(1-a)}$ for all types j.

Substituting these demand curves and prices into (5) and (6) yields the following present values

$$V^s(t) = ((1-a)/a)L^s(a^2)^{1/(1-a)}\int_t^\infty e^{-r(v,t)(v-t)}dv \,, \tag{7}$$

$$V^u(t) = ((1-a)/a)L^u(a^2)^{1/(1-a)}\int_t^\infty e^{-r(v,t)(v-t)}dv \,. \tag{8}$$

Free entry guarantees that $V^s(t)\leq\Gamma^s(N/R)$ and $V^u(t)\leq\Gamma^u(M/R)$. If the value of developing a new intermediate good were greater than the cost, entry would occur until the marginal good (N or M) cost the present discounted value of profits from development. When the benefits of R&D do not equal or exceed the costs, the variety of the relevant good (N or M) is unchanged; this corresponds to the assumption that knowledge is irreversible.

Basic Research

The level of basic research knowledge in the economy, denoted by R, is a key determinant of the costs of developing new "production processes", i.e. higher levels of R lower the costs of developing new intermediate goods. Since the focus of this paper is the adoption of skill or unskilled biased technologies, R could simply grow according to a deterministic trend without altering any of the results below on the relationship between wages or productivity growth and the supply of skilled workers. However, a simple endogenous growth model is adopted instead. Specifically, basic research R is supported by the government, with current government spending (G) adding to the stock of basic research knowledge:

$$dR/dt = G \ . \qquad (9)$$

Government spending is financed through a tax (τ) on the economy's net output (final output not used for intermediate goods production)

$$G = \tau(Y - NX - MZ) \ , \qquad (10)$$

where Y is final output, and the fact that all N or M intermediate good types are used in quantity X or Z is exploited.

Note that in this model G is a pure public good; government spending adds to the stock of basic research knowledge, and this stock of research knowledge is used for the development of new intermediate goods (in a non-rival, non-excludable manner). As emphasized in Barro and Sala-i-Martin (1995), the pure public good model of government expenditures, if relevant anywhere, is arguably most relevant when considering government support of basic research.

Consumers

I simply assume the consumers save a constant fraction of their income, s, as is common in the simplest growth models (and preserves much of the intuition from models in which savings is endogenous; see Barro and Sala-i-Martin (1995)). Households' assets consist of the market values of the intermediate goods firms, $MV^u(t) + NV^u(t)$. Workers are paid their marginal products, implying that wages for skilled and unskilled workers are given by

$$w^s = N(1-a)(a^2)^{a/(1-a)} \quad (11)$$

$$w^u = M(1-a)(a^2)^{a/(1-a)}. \quad (12)$$

Growth in the wages of skilled workers occurs through growth in the variety of skill complements (N), and growth in the wages of unskilled workers comes through growth of unskilled complements (M).

3. Balanced Growth

The outline of the model above provides all the ingredients needed to analyze balanced growth in skill and unskilled-biased technologies. Along a balanced growth path, the interest rate (r) is constant (from (7) and (8)), and output (Y), the stock of basic research knowledge (R), the varieties of skill and unskilled complements (M and N), and wages grow at the same rate; denote this growth rate by γ. The conditions determining this balanced growth path are (after normalizing the labor force (L) to one)

$$Y = (a^2)^{a/(1-a)}(N\omega + M(1-\omega)) \quad (13)$$

$$\Gamma^s(N/R) = ((1-a)/a)(a^2)^{1/(1-a)}\omega/r\ , \quad (14)$$

$$\Gamma^u(M/R) = ((1-a)/a)(a^2)^{1/(1-a)}(1-\omega)/r\ , \quad (15)$$

$$\gamma = \tau(Y - NX - MZ)/R \quad (16)$$

$$\gamma = s(1-\tau)[Y - NX - MZ]/[N(\Gamma^s(N/R)+(M/N)\Gamma^u(M/R))] \quad (17)$$

(13) is the production function, (14) and (15) equate the costs of developing the most advanced intermediate good of either type at each instant to the present discounted value of profits, (16) states the equation for the accumulation of basic research knowledge in growth rate form, and (17) reflects asset market clearing. In particular, since factor prices equal marginal products, households' aggregate income equals the economy's net product ($w^uL^u + w^sL^s + r\{MV^u(t) + NV^s(t)\} = Y - NX - MZ$). Along the balanced growth path, (7) and (8) imply that the values of developing new intermediate goods are constant ($V^u(t)$, $V^s(t)$ constant), and hence equating after-tax savings to the change in household assets implies

$$s(1-\tau)(Y-NX-MZ) = V^s(dN/dt) + V^u(dM/dt).$$

Rearranging this equation, inserting the present values in (14) and (15), and using the balanced growth condition ($\gamma = (dN/dt)(1/N) = (dM/dt)(1/M)$) yields (17).

Substituting the quadratic functional forms for the costs of developing new goods of both types assumed above into (14) and (15) yields the solutions along a balanced growth path for the growth rate, interest rate, and several interesting ratios:

$$N/M = c_1 = [(\delta_2/\delta_1)(\omega/(1-\omega))]^{1/2}, \qquad (18a)$$

$$N/R = c_2 r = s(1-\tau)/[\tau(\omega + (1-\omega)/c_1)a^{2/(1-a)-1}(1-a)]r, \qquad (18b)$$

$$r = [a^{2/(1-a)-1}(\omega/\delta_1)(1-a)]^{1/3}c_2^{-2/3}, \qquad (18c)$$

$$\gamma = \tau c_2^{1/3}[\omega + (1-\omega)/c_1][a^{2a/(1-a)}-a^{2/(1-a)}]. \qquad (18d)$$

These solutions for the balanced growth path are quite intuitive. (18d) indicates that the growth rate is increasing in the exogenous savings rate (a standard result in these endogenous growth models (Barro and Sala-i-Martin (1995)), as more resources available for the expansion in the range of intermediate goods used in production boosts the speed at which new technologies are developed. The growth rate is increasing in the tax rate for low tax rates but then decreasing in the tax rate when the tax rate rises above some level, reflecting the positive influence of government spending on basic research at low tax rates, which is offset at high tax rates by the decrease in funds available for intermediate goods development (see (17)). The interest rate is decreasing in the savings rate (as more savings drive down the return to saving), and increasing in the tax rate (as higher taxes decrease savings).

The novelty of the model herein lies in its distinction between applied and basic research, and especially in the distinction between skill-biased and unskilled-biased applied technologies. (18b) reveals that the ratio of applied to basic "technology" (N/R) is increasing in the savings rate (as savings contribute to the development of applied technologies), decreasing in the tax rate (as taxes are applied to basic research and decrease savings available for applied technology development), and decreasing in the cost of developing applied technologies (represented by δ_1; the intuition is obvious). (18a) indicates that the ratio of skill-biased to unskilled-biased technologies (N/M) is decreasing in the relative costliness of developing the technologies (δ_1/δ_2), and increasing in the relative supply of the complementary labor input ($\omega/(1-\omega)$). In the model, higher wages for skilled labor are assured by assuming that skilled workers have access to a greater number of technologies because such technologies are sufficiently cheaper to produce (δ_1/δ_2 small).

The effect of the relative supply of skilled labor on N/M is a key implication of the model with regard to the differences across steady states in the relative wages of skilled and unskilled labor. Since more skill-biased technologies relative to unskilled-biased technologies are developed along a steady state with a higher share of skilled labor (ω), wages for skilled labor are *higher* relative to wages of unskilled labor in an economy with a greater share of skilled labor (since the relative wages of skilled labor are increasing in the ratio of skill to unskilled-biased technologies (N/M) from (11) and (12)). This is exactly the opposite of the standard supply and demand story told in models with exogenous biases in technologies, where increasing the supply of skilled labor lowers skilled labors' relative wages. The difference arises because, under endogenous technology development, more technologies are developed to complement a factor of production when the number of the complementary factor increases. This effect makes sense; after all, technologies are not going to be developed if there is no one to use the technology.

4. A Brief Tour of the Relevant Evidence

To explore whether the type of model presented above is at least qualitatively consistent with historical experience, it is useful to compare the predictions of the model with experience, as well as discuss further the relationship of the model herein to previous models of skill-biased technological change. The initial focus is on the consistency of the model with the behavior of wages and models of skill-biased technological change, followed by a brief discussion of the implications of the model for output growth.

Wages and Skill-Biased Technological Change

First, the model is clearly capable of explaining the challenge posed in Mincer (1993) and the introduction of a lack of a downward trend in the return to education and increases in the skill wage premium in the face of massive increases in the skill composition of the workforce over long time horizons; the model implies that more skilled workers raise the skill premium in the steady state because of the endogenous development of more technologies for skilled labor. In effect, a higher share of skilled labor shifts the demand for skilled labor through more investment in technologies appropriate for skilled labor.

Another interesting challenge lies in the effects of an exogenous change in the share of skilled labor on the growth of each type of technology and the relative wages of skilled and unskilled labor along the transition to the steady state. Why is this an interesting question? The relative supply of skilled labor rose dramatically in the U.S. during the 1970's, at least in part exogenously due to government support for higher education (Becker (1993), Juhn, Murphy, and Pierce (1993), and Mincer (1993,1995)). In the 1980's, the relative wages of skilled labor rose and unskilled wages stagnated (despite the fact that the share of the labor force with skills was at all-time highs (Bound and Johnson (1995)), an effect that is largely attributed to exogenous skill-biased technological change (Katz and Murphy (1992), Juhn, Murphy, and Pierce (1993) and Mincer (1993,1995)).

Suppose that the economy is in a balanced growth steady state as above, and then the share of skilled labor exogenously increases. Equations (7) and (8) imply that an increase in ω leads immediately to a higher present discounted value of investments in skill-biased technologies, and a lower present discounted value of investments in unskilled-biased technologies. Since N/M and M/R are fixed at the time of the initial increase in ω, the lower return to investment in unskilled-biased R&D implies that unskilled-biased R&D is halted the instant of the increase in ω (because the complementary factor of production is now in shorter supply and M/R is too high), whereas skill-biased technological change proceeds. Therefore, N/M rises and M/R falls (because government investment in basic research proceeds). The fall in M/R lowers the cost of unskilled-biased technology change, eventually leading to more investment in unskilled technology, but along the transition path skilled wages rise and unskilled wages stagnate. In contrast to previous work, these shifts in technological development arise as a response to other shifts in the economy, rather than exogenously.

While the model is consistent with the eventual rise in the relative wages of skilled labor following the surge in the supply of skilled labor in the 1970's, the immediate response of the relative wages of skilled labor found in the U.S. data in the 1970's was a drop, consistent with a traditional supply and demand story (Katz and Murphy (1992), Juhn, Murphy, and Pierce (1993)). This finding may not be too damaging to the plausibility of the model for a couple of reasons. First, the model herein essentially focuses on long-run trends, and the implication that skilled labor's relative wages increase starting the instant of an increase in the supply of skilled labor stems from the immediate accumulation of more skill-biased technologies and abandonment of investment in unskilled-biased technologies. In reality, this type of technological adjustment presumably takes time, and during adjustment there may be downward pressure on the wages of skilled labor through the traditional supply channel. The second reason this evidence may not be too damaging to the model lies in Machin and Manning's (1997) claim that the initial impact effect of an increase in the supply of skilled labor on wages, as traditionally estimated, is biased downward.[6] After making a correction for this downward bias, Machin and Manning (1997) actually find no evidence of a drop in the wages of more educated workers following a surge in the supply of more educated workers in the UK during the late 1980's; in fact, their point estimates imply a positive effect.[7] The model herein would suggest that the passage of time would result in further increases in the wage premium for more educated workers in the UK as technology development heads towards a new steady state with a higher ratio of skill-biased to unskilled-biased technologies (N/M).

A final set of evidence on skill-biases in technologies comes from Bartel and Lichtenberg (1987), who find that skilled workers implement more new technologies than unskilled workers. The model above is completely consistent with this evidence. Specifically, it was assumed above that the costs of developing new goods was such that the wages of skilled workers were higher than those of unskilled workers, which requires that the stock of technologies available to skilled workers exceeds the stock available to unskilled workers (N>M). Since both N and M grow at the same rate γ in the steady state, the increase in the stock of new skill-biased and unskilled biased technologies are $N\gamma$ and $M\gamma$, respectively. Therefore, along the balanced growth path more skill-biased technologies than unskilled-biased technologies are introduced at each instant.

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[6] On possible source of a downward bias lies in heterogeneity in the quality of skilled workers. For example, if the best quality workers acquire skills first, an increase in the supply of skilled workers will lower the average quality of skilled workers, placing downward pressure on the average wage of skilled workers.

[7] Of course, the interpretation of this result in light of the model requires that the increase in skilled workers was exogenous. Machin and Manning (1997) argue that the surge in more educated workers in the UK during the late 1980's was an exogenous response to reform in the educational system.

While the model herein is consistent with Bartel and Lichtenberg's (1987) evidence, the model herein is quite different from the typical model justified through appeal to Bartel and Lichtenberg (1987). The typical model follows the ideas in Nelson and Phelps (1966), Greenwood and Yorukoglu (1996), Greenwood (1996), and Galor and Tsiddon (1997) that skilled labor makes adoption of new technologies easier, and therefore a rapid burst of exogenous progress first benefits skilled labor (through the adoption phase), and later benefits unskilled labor. The difference is that herein the skill-bias in a technology is endogenous, and depends both on the cost of developing the technology, and the potential demand for the use of the technology, implying that the skill-biases in new technology adoption respond to the skill characteristics of the adopting workforce.

Output Growth

A shift in the labor force shares of skilled and unskilled labor increases wage inequality above because of the acceleration of skill-biased technological change accompanying an expansion in skilled labor. The acceleration can also generate a deceleration in output growth, at least temporarily. To see this, note that the production function relationship (13) (which holds at each instant) implies

$$(d\ln Y/dt) = [N\omega/(N\omega + M(1-\omega))](d\ln N/dt) + [M(1-\omega)/(N\omega + M(1-\omega))](d\ln M/dt)$$

which simply states that the growth in output equals the weighted sum of growth in skill and unskilled-biased technologies, where the weights are the shares of output produced by skilled and unskilled labor. As discussed above, growth in unskilled-biased technologies halts the instant of an increase in skilled labor's share of the workforce (ω), as investment is channeled towards skill-biased technologies ($d\ln M/dt=0$). Such a shift can generate a deceleration in output growth if the share of output produced with skilled labor is initially small (ω small), because the growth in skill-biased technologies ($d\ln N/dt$) is bounded by the availability of savings for investment, but ω can be arbitrarily small initially.

In words, the acceleration of productivity growth in the skilled sector ($d\ln N/dt$) can lead to lower aggregate output growth if the share of output produced by the skilled sector is small. This deceleration in output growth occurs because the unskilled sector is not growing (at least temporarily), and this sector produces a large share of output. This result suggests that, at least qualitatively, a model of endogenous growth in both skill and unskilled-biased technologies is consistent with both rising wage inequality and a period of slow growth following an increase in skilled labor's share in the U.S. during the 1970's. Of course, if ω is initially large, growth could accelerate as the acceleration in skill-biased technological change then may affect a sufficiently large share of the economy to raise aggregate output growth.

5. Summary

The model of this paper is highly stylized. However, the highly stylized framework yields intuitive insights into the process of skill-biased technological change. It makes perfect sense that more skill-biased technology will be adopted when the supply of the complementary factor, skilled labor, rises. If the skill-biased technology sector is a small share of the economy, the shift in resources towards the skilled sector may depress output growth initially. In addition, the endogenous increase in skill-biased technology works against the increased equality of wages for skilled and unskilled workers that arises when the supply of skilled labor rises and technology is exogenous. This endogenous response should generate caution among those who advocate increasing the share of skilled workers in the economy as a measure to raise the relative wages of the unskilled; when endogenous technology choice is allowed, increasing the share of skilled labor in the economy can leave unskilled labor's wages even farther behind skilled labor's wages, as technological innovation for unskilled labor is temporarily abandoned. The available evidence on wages and skill-biased technological change does not appear inconsistent with the basic implications of the model, but a lot more work needs to be done. This paper is simply a first step away from the literature's strong reliance on the notion that the development and adoption of new technologies is inherently skill-biased.

Potential extensions to the model herein include endogenous consumption determination and endogenous skill adoption by workers. These extensions would allow both a welfare analysis, rather than the current focus on the relative wage of the unskilled, and raise the question of whether high and low skill equilibria are possible (due to the increase in the return to skill that accompanies more skilled workers). In addition, more general substitution assumptions for the skilled and unskilled production processes are important to consider, as the perfect substitutes assumption ensures that the prices of goods produced by unskilled and skilled labor are identical, whereas relative price changes (rising relative prices of products produced by unskilled labor) may counteract the expanding wage inequality that can arise under the perfect substitutes assumption.

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