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Why Do New Technologies Complement Skills? Directed Technical Change and Wage Inequality*

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Abstract

A high proportion of skilled workers in the labor force implies a large market size for skill-complementary technologies, and encourages faster upgrading of the productivity of skilled workers. As a result, an increase in the supply of skills reduces the skill premium in the short-run, but then it induces skill-biased technical change and increases the skill premium, possibly even above its initial value. This theory suggests that the rapid increase in the proportion of college graduates in the United States labor force in the 1970s may have been a causal factor in both the decline in the college premium during the 1970s and the large increase in inequality during the 1980s.

Keywords Endogenous Technical Change, Relative Supply of Skill, Returns to Education, Skill-Biased Technological Change, Skill-Technology Complementarity, Wage Inequality.

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I. Introduction

In 1970s college graduates earned 55 percent more than high school graduates. This premium fell to 41 percent in 1980, but then increased to 62 percent in 1995 (Autor, Katz and Krueger [1997]). One explanation for the rapid increase in the college premium in the 1980s is skill-biased technological change. According to this explanation, new technologies are by their nature complementary to skills, so there has always been some skill-biased technical change, and the recent past witnessed rapid introduction of new technologies, leading to an acceleration in skill-bias.[1] Empirical support for this view includes Autor, Katz and Krueger [1997] who calculate that the relative supply of college equivalent workers (college graduates plus half of those with some college) increased by 2.73 percent per year between 1940 and 1970, and increased much faster between 1970 and 1995, by 3.66 percent per year. In contrast, the college premium fell by 0.63 percent per year during the first period and increased by 0.92 percent per year between 1970 and 1995, indicating a much more rapid increase in the demand for college graduates during the last twenty five years.

The skill-bias change explanation leads to a number of questions. Why did skill-biased change accelerate soon after an unprecedented increase in the supply of skills during the 1970s? More striking, Katz and Murphy write "for the 1963-87 period as a whole and most strongly for the 1980s, the groups with the largest increases in relative supplies tended to have the largest increases in relative wages" [1992, p. 52]. Why is this? And related to these questions, why do new technologies complement skills? There are in fact many examples in the eighteenth and early nineteenth centuries of new technologies replacing rather than complementing skills, such as the spinning jenny, weaving machines, Jacquard's loom, printing cylinders, and later the assembly line (see Mokyr [1990]). Current technologies also are not skill-complementary by nature. Computers, for example, simplify some formerly complex tasks such as inventory control and can be used by unskilled workers, as they often are in fast food restaurants and supermarkets.

Motivated by this reasoning, this paper starts from the premise that new technologies are not complementary to skills by nature, but by design. I show that a natural model in which the direction of technical change is endogenous can explain why the demand for skills and the college premium first fell and then increased sharply following the large increase in the supply of skills, and also why as opposed to the skill replacing

[1] For example, Bound and Johnson [1992], Berman, Bound and Grilliches [1994], Caselli [1997], Galor and Tsiddon [1997], Krusell, Ohanian, Rios-Rull and Violante [1997]. See Griliches [1956], Bartel and Lichtenberg [1987] and Goldin and Katz [1998] for micro estimates of technology-skill complementarity, and Krueger [1993] on the impact of computers on the structure of wages.

technological advances of the eighteenth century, today most new technologies appear to be skill-complementary.

Most technologies, once invented, are largely nonrival goods. They can be used by many firms and workers at low marginal cost. When there are more skilled workers, the market for skill-complementary technologies is larger. Therefore, the inventor will be able to obtain higher profits, and more effort will be devoted to the invention of skill-complementary technologies.[2] As a result, the impact of an increase in the supply of skills on the skill premium is determined by two competing forces: the first is the conventional substitution effect which makes the economy move along a downward sloping relative demand curve. The second is the *directed technology effect,* which shifts the relative demand curve for skills as shown in Figure I, because the increase in the supply of skills induces faster upgrading of skill-complementary technologies.

A large increase in the supply of college graduates as in the late 1960s and 1970s first moves the economy along a short-run (constant technology) relative demand curve, reducing the college premium. The relative supply change also increases the size of the market for technologies complementary to skills, and induces a change in the direction of technical progress and a shift of the relative demand curve in Figure I. Suppose first that the substitution effect dominates the directed technology effect. In this case, the college premium first falls and then increases, but never above its initial level. In contrast, if the directed technology effect is sufficiently strong, the model predicts that in the long-run the college premium should *increase.* This is the case drawn in Figure I and offers a more complete explanation for the changes in the U.S. college premium over the past twenty five years. I will also show how this mechanism can account for a puzzling aspect of the recent changes in the structure of wages; the increase in residual wage inequality during the 1970s while the college premium was falling. Therefore, the analysis in this paper suggests that the unprecedented increase in the supply of college graduates during the 1970s may have been causal both for the technological developments and the changes in the structure of wages of the past two decades. Finally, since the proportion of skilled workers has increased substantially over time, this theory also suggests a natural reason why new technologies should be more skill-complementary today than two centuries ago, and accounts for the steady increase in the demand for skills in the face of rapidly increasing supply of skills over the past century.

There are other episodes in which a large increase in the supply of skills appears to

[2] Economic motives do not play a direct role in all inventions. “Macroinventions”, to use Mokyr’s [1990] term, are likely to be exogenous and stem from advances in basic science. For the thesis in this paper, it is sufficient that economic motives influence the direction in which these macroinventions are developed.

have affected the direction of technical change. High school enrollment and graduation rates doubled in the 1910s, mostly due to changes in the location and curricula of schools and the decline in transport costs (Goldin and Katz [1995]). The skill premium (white collar wage relative to blue collar wage) fell sharply in the 1910s. Yet, despite the even faster increase in the supply of high school skills during the 1920s, the skill premium levelled off and started a mild increase. Goldin and Katz [1995] conclude that the demand for high school graduates must have expanded sharply starting in the 1920s, presumably due to changes in office technology and higher demand from new industries such as electrical machinery, transport and chemicals.

Thought experiments with exogenous variation in skills illustrate the main ideas, but in the long run the supply of skills responds to changes in the skill premium. The model developed in this paper allows me to simultaneously endogenize the demand for and the supply of skills. When the directed technology effect dominates, an increase in the supply of college graduates again first depresses and then increases the college premium, but now it also encourages more workers to enroll in college, and induces an extended period of adjustment where the supply of skills and skill-complementary technologies increase together.

An analysis of the implications of international trade on wage inequality provides another application of this theory. The key observation is that trade affects the direction of technical change. If the United States starts trading with the Less Developed Countries (LDCs) and sells technologies to LDC firms, the size of the market for technologies complementary to unskilled labor increases and wage inequality declines, or at most increases by only a small amount. However, if due to lack of international property rights protection, it is not possible to sell new technologies to LDC firms, trade simply increases the relative price of the skill intensive goods, inducing further effort in upgrading skill-complementary technologies. I show that in this case conventional calculations underestimate the impact of trade on wage inequality because they ignore the change in the direction of technical change induced by trade.

This paper is related to the older literature on induced innovations, including theoretical work by Kennedy [1964] and Samuelson [1970], empirical studies by Schmookler [1966] and Hayami and Ruttan [1970], and historical work by Habakkuk [1962] and David [1975]. These studies discuss the impact of factor prices on innovations. I treat factor prices as endogenous and point out the importance of market size. The market size effect —the fact that an increase in the number of skilled workers increases the size of the market for skill-complementary technologies— is crucial in deriving the main result of the paper, which is that a larger relative supply of a factor can lead to faster upgrading of technologies complementary to this factor. Previous papers would predict the opposite result because they do not feature the market size effect. My paper also builds on and extends the work of Romer [1990], Aghion and Howitt [1992] and Grossman and Helpman [1991] on endogenous technical change by including two types of workers, each using different technologies and allowing technological change to be directed. Finally, a number of recent papers also suggest that changes in the supply of skills may change the demand for skills. In Acemoglu [1996], when there is a sufficient fraction of workers who are skilled, firms find it profitable to create jobs specifically targeted for this group, and as a result, unskilled wages fall and skilled wages increase. Krugman [1997] has recently constructed a signalling model with some common features. Independent work by Kiley [1997] considers an expanding varieties model and shows that an increase in the supply of skills can create skill-biased technical change and increase inequality. Walde [1997] compares the technology choice of economies differing with regards to the skill level of their high school graduates. He shows that an economy with less skilled high school graduates may choose a technology which makes little use of high school skills and have a high skill premium.

The plan of the paper is as follows. Section II analyzes the basic model and contains the most important results of the paper. Section III shows how the model can account for the increase in residual wage inequality during the 1970s while the college premium declined. Section IV endogenizes the relative supply of skills. Section V discusses the impact of international trade on the direction of technical change and wage inequality. Section VI concludes.

II. The Basic Model

I first outline the standard part of the model and explain the main results informally. The formal model follows Aghion and Howitt [1992] and Grossman and Helpman [1991], but allows the pace of technological improvements in skill-complementary and labor-complementary machines to differ.

A. Preliminaries and Outline

H skilled workers and L unskilled workers supply labor inelastically and have identical preferences over the unique consumption good, y:

$$U_k(t) \equiv \int_t^\infty \exp(-r(\tau - t))c_k(\tau)d\tau \qquad (1)$$

where $c_k(\tau)$ is the consumption of agent k at time τ and r is the discount rate, and due to linear utility, it is also the interest rate. I will drop the time argument when this causes no confusion.

The consumption good is produced from two complementary intermediate goods, or production processes, one using skilled and the other unskilled labor. The market for intermediate goods is competitive. I denote the total output of these intermediate goods by Y_l and Y_h, and the aggregate production of the consumption good is:

$$Y = \left[Y_l^\rho + \gamma Y_h^\rho\right]^{1/\rho}, \tag{2}$$

where $\rho \leq 1$, so the elasticity of substitution between Y_l and Y_h is $1/(1-\rho)$. I normalize the price of the final good in each period to 1, and denote the prices of the two intermediate goods by p_l and p_h. Competitive pricing gives a standard relative demand equation for intermediate goods:

$$p \equiv \frac{p_h}{p_l} = \gamma \left(\frac{Y_l}{Y_h}\right)^{1-\rho}. \tag{3}$$

There are m_l and m_h firms in the two intermediate goods sectors, and for now, I normalize $m_l = m_h = 1$. Since later there will be constant returns to variable factors, the number of firms does not matter. The production of Y_h, the skill-intensive good, requires skilled labor while the production of the labor intensive good, Y_l, requires unskilled labor. Namely, firm i in sector s has production function:

$$y_s(i) = A_s(i) n_s(i)^\beta, \tag{4}$$

where $s = l, h$, and $n_s(i)$ is the number of workers employed by firm i in sector s, $\beta < 1$, and $A_s(i)$ is the productivity of labor in this firm. The labor market is competitive and clears at every instant. Since firms in sector l only employ unskilled workers, and those in sector h only hire skilled workers, market clearing implies that $\int n_l(i)di \equiv N_l = L$ and $\int n_h(i)di \equiv N_h = H$. The profits of these firms, if any, are redistributed to consumers.

Firm level productivity, $A_s(i)$, is determined by the technologies employed by the firm, and skilled and unskilled workers use different technologies. Leaving a detailed discussion to the next subsection, for now note that all firms in a sector face the same (strictly concave) problem, so in equilibrium $A_s(i) = A_s$, and wages in terms of the final good are: $w_s = \beta p_s A_s N_s^{-(1-\beta)}$ for $s = l, h$.

The skill premium —skilled wage, w_h, relative to unskilled wage, w_l— is the main interest for this paper. Using (3), this skill premium, ω, is:[3]

$$\omega \equiv \frac{w_h}{w_l} = \gamma \left(\frac{A_h}{A_l}\right)^\rho \left(\frac{H}{L}\right)^{-(1-\beta\rho)}. \tag{5}$$

[3] In this section, for some parameter values, skilled workers may have lower wages than the unskilled,

The skill premium increases when skilled workers become more scarce, i.e. $\frac{\partial\omega}{\partial H/L} < 0$. This is the usual substitution effect, and shows that for given technology, the relative demand curve for skill is downward sloping with elasticity $-1/(1-\beta\rho)$. Moreover, when $\rho \in (0,1]$, $\frac{\partial\omega}{\partial A_h/A_l} > 0$, that is, improvements in the skill-complementary technology increase the skill-premium. The converse is obtained when $\rho < 0$. The conventional wisdom is that the skill-premium increases when skilled workers become more, not less, productive, which is consistent with $\rho > 0$. Most estimates reveal an elasticity of substitution between skilled and unskilled workers greater than 1 which also implies $\rho > 0$.[4] Therefore, in the remainder of the paper I focus on the case $\rho \in (0,1)$, though the formal analysis does not depend on this parameter restriction.

The main story of the paper can now be told informally. As shown in detail in the rest of this section, endogenous technical progress implies that:

$$\frac{A_h}{A_l} = f\left(p, \frac{H}{L}\right). \tag{6}$$

Namely, the relative productivity of skilled workers depends on the relative price of the skill-intensive good ($p \equiv p_h/p_l$) and the relative supply of skilled workers (H/L). The former effect is similar to the impact of factor prices on technical change which was emphasized by the literature on induced innovations cited in the introduction. Intuitively, when a good becomes more expensive, technologies used in its production command a higher price, increasing the incentives to upgrade these technologies. Since an increase in H/L reduces p, this effect further depresses the skill premium in response to a rise in H/L.

The innovation of this paper is the second term in f. The size of the market for skill-complementary technologies relative to the market size of technologies complementary to unskilled labor is proportional to H/L. Therefore, an increase in H/L makes the invention of a new technology complementing skills more profitable and increases A_h/A_l, so $\frac{\partial A_h/A_l}{\partial H/L} > 0$. The formal analysis below will establish that as long as $\rho > 0$, this second effect dominates the price effect, therefore, $\frac{dA_h/A_l}{dH/L} = \frac{\partial A_h/A_l}{\partial p}\frac{\partial p}{\partial H/L} + \frac{\partial A_h/A_l}{\partial H/L} > 0$. This is

i.e. $\omega \leq 1$. One may want to impose $\gamma > (H/L)^{1-(1-\beta)\rho}$ to avoid this, or alternatively, one could assume that skilled workers can use the machines designed for the unskilled and be more productive at this than the unskilled. When the supply of skills is endogenized in Section IV, the skill premium is always positive, so this parameter restriction is not necessary.

[4] See Freeman [1986]. Practically, all estimates of the aggregate elasticity of substitution between high and low education workers are between $\sigma = 1$ and 2. These estimates control for time trends in the demand for skills or use cross-sectional data, thus in terms of the model here they correspond to the constant technology elasticity. So $1/\sigma = 1 - \beta\rho < 1$, and $\rho > 0$. Since a large part of the substitution between skilled and unskilled workers is within industries, ρ should not be interpreted as the elasticity of substitution between different goods.

the essence of the directed technology effect: an increase in the relative supply of skilled workers leads to an improvement in the technologies used by skilled workers.

Since technology is given in the short-run, an increase in H/L first leaves A_h/A_l (mostly) unchanged and reduces the skill premium. Then, the direction of technical progress changes due to the market size effect. As a result, the skill premium rebounds from its short-run low. Moreover, if the directed technology effect is sufficiently pronounced, the skill premium may rise above its initial level, as drawn in Figure I. The rest of this section models the R&D sector more formally, demonstrates that technical change takes the form summarized in equation (6), and analyzes the dynamic response of the skill premium to an increase in H/L.

B. Technological Advances

Firm level technology, $A_s(i)$, is determined by the quality and quantity of machines used. There is a continuum $j_s \in [0,1]$ of machines for each sector. The fact that each sector uses different machines is the sense in which skilled and unskilled workers use different technologies. The quantity of machine j that firm i in sector s uses is denoted by $x_s(i,j)$. Machines, the only form of capital in this economy, depreciate fully after use, which simplifies the analysis. I denote the currently available highest quality of machine j in sector s by $q_s(j)$. Incorporating the fact that outdated machines will not be used (which is true in equilibrium as shown below), the productivity of firm i takes the form:

$$A_s(i) = \frac{1}{1-\beta} \int_0^1 q_s(j) x_s(i,j)^{1-\beta} dj. \tag{7}$$

Notice that (4) and (7) imply that production of Y_h and Y_l is subject to constant returns to scale. The presence of a continuum of machines in (7), rather than just one per sector, simplifies the analysis. First, it implies that innovators do not have to take their impact on factor prices into account. Second, it ensures that the growth rate of the economy is deterministic.

Firms (producing y_l and y_h) purchase machines and labor to maximize static profits. Let us denote the price of machine of quality $q_s(j)$ by $\chi_s(j)$. Since there are no adjustment costs, firm i's problem at all points in time is:

$$\max_{n_s(i), x_s(i,j)} \; p_s A_s(i) n_s(i)^\beta - \int_0^1 \chi_s(j) x_s(i,j) dj - w_s n_s(i).$$

The solution of this problem implies that the aggregate demand for machine j in sector s is $X_s(j) = \left[p_s q_s(j) N_s^\beta / \chi_s(j)\right]^{1/\beta}$ where $N_h \equiv H$ and $N_l \equiv L$.

Technological advances take place as in Aghion and Howitt [1992] and Grossman and Helpman [1991]. When there is an innovation for machine j, the quality of the machine increases by a factor $\lambda > 1$. I further assume that $\lambda > (1-\beta)^{-(1-\beta)/\beta}$, which is a simplifying assumption to be discussed in the next subsection. The R&D firm which innovates has a monopoly right over that particular vintage (e.g. it holds a perfectly enforced patent), so it can charge a profit maximizing price and sell as many units of the newly discovered input as it wishes. The marginal cost of producing input $q_s(j)$ is $q_s(j)$, so it increases linearly with the quality of the machine.

Innovations are the result of R&D carried out by research firms using only final output as factor of production. There is free-entry into the R&D sector. If the total amount of R&D activity in technology j for sector s is z, then the probability of innovation is $z\phi(z)$. The marginal cost of R&D effort for inventing a machine of vintage $q_s(j)$ is $Bq_s(j)$ (in terms of the final good).[5] $z\phi(z)$ is nondecreasing, i.e. $\phi(z) + z\phi'(z) \geq 0$, and $\phi(.)$ is everywhere smoothly decreasing, which implies decreasing returns to R&D effort (see the Appendix for the case of constant returns scale, $\phi(z) \equiv 1$). Also, I impose $\lim_{z\to 0} \phi(z) = \infty$ and $\lim_{z\to\infty} \phi(z) = 0$. These Inada type restrictions on $\phi(.)$ ensure an interior solution and smooth dynamics.

C. Equilibrium R&D Effort

The aggregate demands for technology characterized above are isoelastic, so the profit maximizing price is a constant markup over marginal cost: $\chi_s(j) = q_s(j)/(1-\beta)$ for vintage $q_s(j)$. The assumption that $\lambda > (1-\beta)^{-(1-\beta)/\beta}$ implies that even if the next best technology, $\hat{q}_s(j) = q_s(j)/\lambda$, were sold at marginal cost, firms would prefer to buy $q_s(j)$ sold at the monopoly price, ensuring that the monopoly pricing policy is optimal (see Grossman and Helpman [1991]).

Given monopoly prices, every firm in the relevant sector buys: $x_s(i,j) = X_s(j) = \left[(1-\beta)p_s N_s^{\beta}\right]^{1/\beta}$. Therefore, the equilibrium productivity in sector s, (7), can be written as: $A_s = \frac{1}{1-\beta} Q_s \left[(1-\beta)p_s N_s^{\beta}\right]^{(1-\beta)/\beta}$, where I have defined:

$$Q_s \equiv \int_0^1 q_s(j)dj,$$

[5] Equivalently, the cost of R&D effprt to improve vintage $q_s(j)$ is $B\lambda q_s(j)$. The assumption that R&D inputs are in terms of final output serves to highlight that changes in skill premium are not driven by changes in the level of R&D activity. If R&D uses more skilled labor, then the skill premium will increase in periods of high R&D activity, similar to "skill-biased technology adoption" effect emphasized in Nelson and Phelps [1966], Galor and Tsiddon [1997], and Greenwood and Yorukoglu [1997], but this does not change the main results of the paper.

for $s = l, h$. Q_l and Q_h are the average qualities of machines used in the labor and skill-intensive sectors, and are the relevant measure of technological know-how and the key state variables of this economy.

The value of owning the leading vintage of machine j of sector s is:

$$rV_s(j) = \pi_s(j) - z_s(j)\phi(z_s(j))V_s(j) + \dot{V}_s(j), \tag{8}$$

where $z_s(j)$ is the current aggregate R&D effort to improve machine j in sector s and $\pi_s(j) = \beta X_s(j)q_s(j)/(1-\beta)$ is the flow profit. At the flow rate $z_s(j)\phi(z_s(j))$, the firm loses its monopoly position because there is a new innovation, and the time derivative of V in (8) takes care of the fact that $z_s(j)$ may be time varying. Finally, free-entry into R&D activities implies:

$$\phi(z_s(j))V_s(j) = Bq_s(j), \tag{9}$$

where the left-hand side is the marginal return to higher R&D effort directed at this machine, and the right-hand side is the marginal cost.[6]

An equilibrium in this economy requires that firms rent the profit maximizing amounts of all inputs, innovators follow the profit maximizing pricing policy, product, intermediate good and labor markets clear, and there is no opportunity for any research firm to enter (or exit) and increase its profits. Equations (3), (5), (8) and (9) ensure these conditions.

D. Characterizing the Equilibrium

Let us start with the balanced growth path (BGP) where all variables either grow at a constant rate or are time invariant. In particular, since V denotes the value of an existing frontier technology, we have $\dot{V} = 0$. Then, equations (8) and (9) imply that in BGP:

$$\frac{\beta}{1-\beta} p_s^{1/\beta} N_s = B\left(\frac{r + z_s(j)\phi(z_s(j))}{\phi(z_s(j))}\right) \tag{10}$$

for all $j \in [0, 1]$ and $s = l, h$. This equation states that innovation effort for machine j is higher when profits from technology sales, the left-hand side, are higher. The profits will be higher in turn when the price of the product is higher and/or when more workers

[6] There is free-entry by small R&D firms which ignore their impact on the invention probability of other firms working to improve the same machine. If there had been one large firm doing R&D on each machine, the left-hand side of (9) would have been $\left[\phi'(z_s(j))z_s(j) + \phi(z_s(j))\right] V_s(j)$. The choice between these two formulations does not change the results. Also (9) ignores the constraint that total expenditure on R&D should not exceed current output. Assuming that ϕ is sufficiently decreasing would ensure that this constraint never binds. Alternatively, this constraint does not apply if the economy can borrow from abroad at the rate r.

use this technology. It also immediately follows from (10) that $z_s(j) = z_s$ for all j. In other words, the BGP levels of effort for all skill-intensive (labor intensive) technologies are the same, so we only have to determine two variables, z_l and z_h.

Combining (10) for $s = l$ and $s = h$, we see that z_h/z_l, relative research effort at skill-complementary technologies, is increasing in $p\,(H/L)^{\beta}$, as captured by the reduced form equation $f(p, H/L)$ above. The price effect has exactly the same intuition as before: when p_h is high relative to p_l, it is more profitable to invent skill-complementary technologies because their output is more expensive. Simple algebra using (3) and profit-maximizing technology choice gives the relative price p as a function of H/L:

$$p = \gamma^{\beta\nu} \left(\frac{Q_h}{Q_l}\right)^{-\beta(1-\rho)\nu} \left(\frac{H}{L}\right)^{-\beta(1-\rho)\nu}, \tag{11}$$

where $\nu \equiv (1-(1-\beta)\rho)^{-1}$. Therefore, an increase in H/L depresses p, and via the price effect, it induces the invention of more labor-complementary technologies. Counteracting the price effect is the market size effect, the second argument of f in (6). When there are more skilled workers, the size of the market for skill-complementary technologies is larger. For $\rho \in (0, 1]$, the market size effect is more powerful.[7]

To determine the dependence of technology on relative supplies more formally, note that there is a continuum of skill-intensive inputs, so $z_h\phi(z_h)$ is exactly the rate of improvements. Hence $(\lambda-1)z_h\phi(z_h)$ is the growth rate of $Q_h \equiv \int_0^1 q_s(j)dj$. Similarly $(\lambda-1)z_l\phi(z_l)$ is the growth rate of Q_l. For BGP, we need Q_h/Q_l to be constant, therefore $z_l = z_h$. Equation (10) then implies that along the BGP:

$$p = \left(\frac{H}{L}\right)^{-\beta}. \tag{12}$$

Intuitively, BGP requires that $z_l = z_h$, so the demand for skill-complementary technologies relative to labor-complementary machines should be independent of H/L, which implies (12). Combining (12) with (11), we see that in BGP, the relative technology of skilled workers needs to satisfy:

$$\frac{Q_h}{Q_l} = \gamma^{\frac{1}{1-\rho}} \left(\frac{H}{L}\right)^{\frac{\beta\rho}{1-\rho}}. \tag{13}$$

[7] To see this note that p is decreasing in H/L with elasticity $\beta(1-\rho)/(1-(1-\beta)\rho)$ which is less than β when $\rho > 0$. Although it is plausible for the market size effect to dominate in the case of skilled and unskilled workers, the price effect may dominate in other situations. For example, Hayami and Ruttan [1970] discuss the different paths of agricultural development in the United States and Japan. The scarcity of land in Japan relative to the United States appears to have induced a faster rate of innovation and adoption of fertilizers, increasing output per acre.

Equation (13) is an important result. Q_h/Q_l is the equilibrium technology level of the skill-intensive sector relative to the labor intensive sector, and depends on the relative abundance of the two types of labor. Since profits to innovation are proportional to market size, they are effectively proportional to the number of workers using the technology. Therefore, when H/L increases, innovation and R&D in the skill-intensive sector become more profitable, inducing Q_h/Q_l to increase (as long as $\rho > 0$). This is the directed technology effect: the greater the fraction of skilled workers in the economy, the greater their productivity relative to unskilled workers. Another implication of (13) is that as the economy accumulates more skills, technical change responds to make new technologies more complementary to skilled labor. Therefore, the fact that the demand for skills has increased steadily in the face of increasing supply of skills over the past century is consistent with the approach in this paper. Also, interestingly, during the eighteenth and early nineteenth centuries, there was a large migration of unskilled workers from villages and Ireland to English cities (see Williamson [1990]). So this increase in the supply of unskilled workers might have played a role in inducing the creation of the well-known skill-replacing technologies of that period.

Returning to the formal analysis, the BGP R&D effort level can now be determined from (10), (12) and (13) by imposing $z_l = z_h = z^*$, which gives:[8]

$$B\left[\frac{r + z^*\phi(z^*)}{\phi(z^*)}\right] = \frac{\beta}{1-\beta}\left[\gamma H^{\frac{\beta\rho}{1-\rho}} + L^{\frac{\beta\rho}{1-\rho}}\right]^{\frac{1-\rho}{\rho\beta}}. \tag{14}$$

Finally, using the analysis so far and (5), we have (proof in the Appendix):

Proposition 1 There is a unique balanced growth path (BGP) where both sectors and total output grow at the rate $(\lambda - 1)z^*\phi(z^*)$ with z^* given by (14). Along the BGP, Q_h/Q_l is given by (13) and the skill premium is:

$$\omega = \gamma^{\frac{1}{1-\rho}}\left(\frac{H}{L}\right)^{\eta}, \tag{15}$$

where $\eta \equiv \beta\rho^2/(1-\rho) - (1-\beta\rho)$.

In the unique BGP there is a 1-to-1 relation between the relative supply of skilled workers and their relative wage. This relation can be either increasing or decreasing.

[8] As in Aghion and Howitt [1992] and Grossman and Helpman [1991], the growth rate increases with total population. This is not important for the focus of this paper. All the results of interest continue to hold if we impose $z_h + z_l = \bar{z}$, which would remove the scale effect. Alternatively, we can impose that for $z \geq \hat{z}$, $z\phi(z) = \phi_0 < \infty$, and the scale effect would disappear once the population reaches a critical threshold. Further, an increase in H/L leaving total population unchanged may increase or decrease the BGP growth rate. The restriction $z_h + z_l = \bar{z}$ also removes the effect of H/L on the growth rate.

The second term in η, $-(1-\beta\rho)$, is the usual substitution effect form equation (5). If technology were exogenous in this economy, i.e. if A_h/A_l (or Q_h/Q_l) were constant, the skill premium would be a decreasing function of H/L. When technology is endogenous, the increase in H/L changes the direction of technical progress, and leads to more R&D activity in the skill-complementary technologies. As a result, Q_h/Q_l increases, and the "short-run relative demand curve" shifts to the right as in Figure I. The long-run relative demand curve is therefore more elastic than the short-run demand curve.[9] Moreover, if $\beta\rho^2/(1-\rho)$, the directed technology effect, is large enough, η is positive, and the long-run relative demand curve for skills is *upward sloping*.[10] In this case, an increase in the supply of skills leads to a higher relative price of skill in the long-run. This "perverse" case is more likely to happen when ρ is close to 1 so that the skill-intensive and labor-intensive production processes (intermediate goods) are close substitutes, and when β is close to 1 so that there are only limited decreasing returns to labor within each sector.

A different intuition for the possibly upward sloping relative demand curve is that there is an important nonconvexity in this economy. There is a fixed up-front cost of discovering new technologies, and once discovered, they can be sold to many firms at constant marginal cost. This nonconvexity (nonrivalry of technology use) implies that it is more profitable to improve technologies designed for a larger clientele. This is the essence of the directed technology effect. Interestingly, the size of this nonconvexity, B, does not matter for this result. Only when $B = 0$, the nonconvexity and hence our results disappear, but in this case the growth rate of the economy becomes infinity. To see the importance of the nonconvexity and market size for the results more clearly, one can consider a modified model where technological monopolists can only sell X units of their machines, where $X < \min\{L,H\}$. The rest of the market will then be filled by imitators who produce a unit of a machine of quality q at the marginal cost $q/(1-\beta)$ (so that all machines sell at the same price, and the profit maximizing price for the monopolist is the same as above). This modification removes the market size effect because an increase in H does not increase the market size of skill-complementary technologies for the innovator. Following the same steps as above, we see that in this case (13)

[9] The long-run relative demand curve is more elastic than the short-run demand curve even when $\rho < 0$, because from (13), an increase H/L reduces Q_h/Q_l, but in this case, as (5) shows, the skill premium is *decreasing* in Q_h/Q_l. So even when $\rho < 0$, an increase in H/L first reduces and then increases the skill premium. However, when $\rho < 0$, the long-run relative demand curve can never slope up.

[10] H/L has two effects on technology: first, it determines the quantities of machines purchased at a given Q_h/Q_l, and second, it changes Q_h/Q_l. The second effect is the important one. To see this, suppose there is no R&D, but A_s is still determined by purchases of machines from a monopolist. In this case, the skill premium is again a decreasing function of H/L, but with the smaller elasticity, $-(1-\rho)/(1-(1-\beta)\rho)$, which is also the short-run elasticity in Proposition 3.

becomes $Q_h/Q_l = \gamma^{1/(1-\rho)}(H/L)^{-1}$. So an increase in H/L only creates the price effect on technological improvements, and causes *slower* upgrading of skill-complementary technologies. The relative demand curve is always downward sloping in this case.

The next proposition summarizes the equilibrium dynamics out of the BGP. Denoting the BGP level of Q_h/Q_l given in (13) by Q^*, we have (proof in the Appendix):

Proposition 2 (a) Locally, there exists a unique transition path converging to BGP, so that if $Q_h/Q_l \neq Q^*$, then z_h and z_l jump, and Q_h/Q_l monotonically adjusts to Q^*. If $Q_h/Q_l < Q^*$, then $z_h > z_l$ along the transition path and vice versa.

(b) Suppose the elasticity of the function ϕ, $\epsilon_\phi(z)$, is nonincreasing in z. Then, for all $Q_h/Q_l \neq Q^*$, there is a globally unique saddle path to BGP along which Q_h/Q_l monotonically converges to Q^*. If $Q_h/Q_l < Q^*$, then $z_h > z_l$ along the transition path and vice versa.

This proposition shows that the BGP is locally (saddle path) stable, and under a fairly weak assumption on the ϕ function, also globally stable. When Q_h/Q_l is below its BGP level, the economy invests more in skill-complementary technologies ($z_h > z_l$), raising Q_h/Q_l toward the BGP.

E. The Dynamic Response to a Relative Supply Shock

The following result summarizes the dynamic response of the economy to an unanticipated relative supply shock (proof in the Appendix):[11]

Proposition 3 Consider an unanticipated increase from H/L to $\delta H/L$ starting from a BGP with skill premium $\omega = \omega_0$. Immediately after the shift, the skill premium falls to ω_{SR}, where $\log \omega_{SR} - \log \omega_0 = -\theta \log \delta$ and $\theta \equiv (1-\rho)/(1-(1-\beta)\rho) > 0$, and z_h/z_l jumps up. The new BGP skill premium ω_{LR} is such that $\log \omega_{LR} - \log \omega_0 = \eta \log \delta$.

Following the relative supply shock, the skill premium falls by $\theta \log \delta$. The short-run response is for given technological know-how because Q_h/Q_l is a stock variable and changes slowly. In terms of Figure I in the introduction, this is a move along the

[11] The increase in the supply of skills during the 1970s may have been anticipated. This does not change the qualitative conclusions reached in Proposition 3. The reason is that it is not profitable to invent skill-complementary technologies much before workers who will use them are in the market, because other firms are likely to improve on these technologies before the original inventor has had access to the larger market.

short-run (constant technology) relative demand curve, causing a decline in the skill premium. As the economy adjusts to its new BGP, Q_h/Q_l increases, and the skill premium starts increasing from its short-term low. In terms of Figure I, the constant technology relative demand curve shifts to the right. Therefore, an increase in the relative supply of skills creates a period of rising skill premium in response to the induced shift in the relative demand for skills. This result is not very surprising: an intuition based on the LeChatelier Principle suggests that the elasticity of substitution between skilled and unskilled workers should increase as other factors are adjusted (Samuelson [1947]). In this paper, the other factors are measures of technology, A_l and A_h, and in the case of $\eta < 0$, the results confirm this intuition. In contrast, when $\eta > 0$, the model's predictions are more surprising and original. Because of the nonconvexity introduced by the market size effect, the increase in H/L has a large impact on A_h/A_l, and eventually raises the skill premium above its initial value.

Proposition 3, especially in the case where $\eta > 0$, offers an alternative explanation for the behavior of the U.S. economy during the past twenty five years. There was a large increase in the supply of skills in the 1970s. Between 1940 and 1970, the relative supply of college equivalent workers grew at the rate of 2.73 percent per year. In contrast, between 1970 and 1980, this relative supply grew almost twice as fast, at 5.19 percent per year (in other words by 52 percent in the course of ten years, see Autor, Katz and Krueger [1997]). This is a very large change in the relative supply of skills preceding the rise in the college premium. Furthermore, these supply changes were at least partly "exogenous" rather than a simple response to anticipated higher returns to education in the future. Enrollment rates had been increasing since the mid 1950s and this trend continued in the 1960s (see Freeman [1976], Figure 6, p. 35). The main reason for the increase in the proportion of college graduates in the labor force during the 1970s was the interaction of these higher enrollment rates with the large cohort sizes arriving in the market during the 1970s. In particular, the cohorts retiring in the 1970s had very few college graduates. For example, only 7.5 percent of those 55 years or older in 1970 were college graduates (Bureau of the Census [1971]). In contrast, due to the enrollment trends dating back to the 1950s, 21.3 percent of those aged 30 to 34 in 1981, a cohort that entered the market between 1970 and 1980, had a college degree (Bureau of the Census [1983]). Moreover, due to the baby boom, the entering cohorts were large relative to the labor force: in 1981 there were 38 million people between the ages of 25-34 as compared to 48.5 million people between the ages of 35 and 54 (Bureau of the Census [1983]).

Two other factors also contributed by increasing the enrollment rates further during the late 1960s and 1970s: (1) until almost the end of the war, the Vietnam era draft laws exempted males enrolled in college from military service. This induced many more young males to stay in college during the late 1960s in order to avoid the draft (Baskir and Strauss [1978]); (2) government financial aid for college increased by a large amount during this era. For example, the total federal aid to college students that stood at approximately 2 billion dollars in 1963 increased to \$14 billion in 1970-71 and then to \$24 billion in 1975-76 (all numbers in 1989-90 dollars, see McPherson and Schapiro [1991]).[12] The theory predicts that in response to this large increase in H/L, the college premium should fall first, and then increase due to the induced skill-biased technical change. This pattern matches the broad behavior of the U.S. college premium from 1970 to the present, and suggests an explanation for why the relative demand for college graduates increased much faster in the past twenty five years than between 1940 and 1970 (Autor, Katz and Krueger [1997]).[13]

The model also predicts that after a large relative supply change, the growth rate of the economy should decline. During adjustment to the new BGP, z_h increases and z_l falls, and because $\phi(.)$ is decreasing —i.e. return to R&D is concave—, the faster technological improvements in skill-complementary technologies do not compensate for the slowdown in the productivity growth of unskilled workers. Therefore, a large increase in H/L not only changes the structure of wages, but also causes a productivity slowdown. Unfortunately, $\phi(.)$, which determines the extent of this productivity slowdown, is not easily observed in the data, so it is not possible to know whether this is an important effect. Greenwood and Yorukoglu [1997] also obtain slower growth during the process of adjustment to new technologies because of costs of adoption and learning. In contrast to that paper, technological change is endogenous here, and the slower growth is due to the fact that the economy invests in improving skill-complementary technologies at the expense of technologies used by unskilled labor.

Finally, it is instructive to do some back-of-the-envelope calculations to see whether the model can generate plausible effects. I take the relative supply shock to be the increase in the ratio of college graduates to high school graduates from 1971 to 1979,

[12] It can be argued however that federal aid increased because the government forecasted the increased need for college graduates. Even if this were the case, which is unlikely, the large part of the increase in the supply of college graduates due to the cohort size effect is still predetermined and "exogenous".

[13] The model does not predict a fall in unskilled wages, which has been a feature of the changes in wage structure during the 1980s. If there is depreciation of existing technologies, for example, because some of the old technologies are not compatible with new ones, the model also predicts that during adjustment to an increase in H/L unskilled wages may fall. See Acemoglu (1996) for an alternative model for the decline in unskilled wages.

since 1971 was the starting year for the large change in the skill composition of the labor force. This gives the relative supply shock, $\Delta \log(H/L) = \log \delta$, as 0.4 (Table VIII in Katz and Murphy [1992]). I take the long-run response to this increase in supply to be the proportional change in the college premium from 1971 to 1987, which is reported as 0.024 by Katz and Murphy [1992]. I compare this number to the long-run response implied by the model, $\eta \log \delta$ $(= \log \omega_{LR} - \log \omega_0)$. I take the "short-run" response to be the change in the skill premium from 1971 to 1979, which is -0.10 (Katz and Murphy [1992]). This number cannot be directly compared to the immediate effect of a one time shock given in Proposition 3 because in reality the supply shock took place over a number of years, so technology must have adjusted during this period. Therefore, I compare it to $(\log \omega_{SR} + \log \omega_{LR})/2 - \log \omega_0$, which is the simple average of the change immediately after the shock and the long-run response.

For a range of parameter choices, the model implies numbers very close to the data. For example, when $\beta = 0.35$ and $\rho = 0.75$, the model yields a short-run elasticity of substitution between college and noncollege workers in the right range and $\eta = 0.06$. This implies a short-term fall in the college premium of 11 percent, comparable to the one in the data and a subsequent large increase, taking it to about 2.5 percent above its initial value. This is quite close to the actual behavior of the college premium. Similar results are obtained when $\beta = 0.4$ and $\rho = 0.73$, or when $\beta = 0.45$ and $\rho = 0.7$. These parameter choices can be given some justification in terms of more micro estimates (see Acemoglu [1997]), but are inherently arbitrary. So these results should be interpreted as purely illustrative. In particular, small changes in ρ change the quantitative implications by a large amount. Also, further increases in H/L in the 1980s make these calculations difficult to interpret.

III. Directed Technical Change and Residual Wage Inequality

Equating skilled workers to those with a college degree, I suggested that a model incorporating the directed technical change can match the evolution of the U.S. college premium. Another important aspect of the changes in the structure of wages is increased residual wage inequality. Using March Current Population Surveys, Juhn, Murphy and Pierce [1993] and Katz and Murphy [1992] find that residual (within group) wage inequality began increasing during the 1970s while the college premium fell. Bernard and Jensen [1997] find the same pattern in the census data. (But DiNardo, Fortin and Lemieux [1996] do not find it using May Current Population Surveys). To date, there has been no unified explanation for the simultaneous increase in residual inequality and the decline in the college premium during the 1970s.[14] In this section, I suggest a simple extension of the model which accounts for this pattern.

Suppose that skills are two dimensional: education and skills unobserved to the econometrician. For lack of a better term, I call the latter ability. A fraction μ_h of college graduates have high ability, and the remainder have low ability. This fraction is $\mu_l < \mu_h$ among low education workers. For example, ability (unobserved skills) could be related to college education, but not perfectly, so that some of the college graduates do not acquire the necessary skills, while some other workers do in spite of not having attended college. Therefore, ability/unobserved skills are not innate, but acquired partly through education. There are H college graduates and L low education workers. Suppose also that the aggregate production function of the economy is:

$$Y = \left[\left(A_{hh} \left(\mu_h H \right)^{\beta} \right)^{\rho} + \left(A_{lh} \left((1-\mu_h) H \right)^{\beta} \right)^{\rho} + \left(A_{hl} \left(\mu_l L \right)^{\beta} \right)^{\rho} + \left(A_{ll} \left((1-\mu_l) L \right)^{\beta} \right)^{\rho} \right]^{1/\rho},$$

which basically combines the equivalent equations to (2) and (4), and also imposes that all firms use the same technology, which is true in equilibrium. The important assumption we make is that A_{hh} and A_{hl} use skill-complementary machines, $q_h(j)$, while A_{lh} and A_{ll} use the $q_l(j)$ machines. For example, $A_{hl} = \frac{1}{1-\beta} \int_0^1 q_h(j) x_{hl}(j)^{1-\beta} dj$ where $x_{hl}(j)$ is the quantity of skill-complementary machine j used in hl. This formulation implies that both high ability college graduates and high ability high school graduates use similar technologies (see Bartel and Sicherman [1997] for some evidence that advanced technologies are complementary to ability/unobserved skills). An analysis similar to the one used previously implies that in BGP:

$$\frac{Q_h}{Q_l} = \left[\frac{\left(\mu_h H \right)^{\beta\rho\nu} + \left(\mu_l L \right)^{\beta\rho\nu}}{\left((1-\mu_h) H \right)^{\beta\rho\nu} + \left((1-\mu_l) L \right)^{\beta\rho\nu}} \right]^{\frac{1}{(1-\rho)\nu}} \tag{16}$$

where $\nu \equiv (1-(1-\beta)\rho)^{-1}$ (see the Appendix for details). The proportion of high ability workers increases the relative abundance of technologies complementary to ability. This has exactly the same intuition as the results in Section II.

Now consider an exogenous increase in H/L over a number of periods. Because $\mu_h > 1/2 > \mu_l$, the proportion of high ability workers in the labor force increases, inducing a rise in Q_h/Q_l. The college premium behaves as in the previous section: first,

[14] Galor and Tsiddon [1997] argue that ability is more valuable in periods of rapid technological change, which offers another explanation for the increase in residual inequality during the 1970s. Caselli [1997] suggests, but does not develop, a related story where due to on-the-job-training, high ability workers benefit from rapid technological change first. Both stories can explain why residual inequality might have grown faster than the college premium during the 1970s, but without further modifications, *not* why college premium fell and residual inequality increased.

it declines for a while in response to the increased supply of H workers. Then, as Q_h/Q_l increases, the college premium also starts increasing, because there is a larger fraction of high ability workers among the college graduates. In contrast to the college premium, which falls first, however, residual wage inequality starts increasing immediately after the shock. To see this, consider the two measures of residual wage inequality in this model, $\omega^h = w_{hh}/w_{hl}$ and $\omega^l = w_{lh}/w_{ll}$, which are the ratios of the wages of high to low ability workers within their education groups. Similar arguments to those developed before imply that:

$$\omega^h = \left(\frac{Q_h}{Q_l}\right)^{\beta\rho\nu} \left(\frac{\mu_h}{1-\mu_h}\right)^{-\theta} \text{ and } \omega^l = \left(\frac{Q_h}{Q_l}\right)^{\beta\rho\nu} \left(\frac{\mu_l}{1-\mu_l}\right)^{-\theta}$$

where θ and ν are as defined above (see the Appendix). Notice that the increase in the supply of college graduates equally affects the numerator and the denominator of the measures of residual wage inequality, ω^h and ω^l, so there is no contraction in residual inequality in response to the increase in H/L. But these measures are proportional to Q_h/Q_l, so the increase in Q_h/Q_l following the change in relative supplies leads to an immediate increase in residual wage inequality.

Therefore, if technologies are complementary to unobserved skills, the approach developed in this paper predicts that in response to increases in the relative supplies of educated workers as in the 1970s, the college premium declines first and then increases, whereas residual wage inequality starts increasing immediately.

IV. Endogenous Supply of Skills

Section II treated the relative supply of skills as exogenous. The increase in the supply of college graduates during the late 1960s and 1970s was argued to be largely exogenous rather than a simple response to anticipated higher returns in the future. Nevertheless, education choices are to some degree forward-looking and respond to returns. It is therefore important to endogenize the supply of skills and verify that the main results are robust. This analysis also provides new results regarding the joint behavior of skills and technology.

Suppose now that a continuum υ of unskilled agents are born every period, and each faces a flow rate of death equal to υ, so that population is constant at 1 (as in Blanchard [1985]). Each agent chooses upon birth whether to acquire education to become a skilled worker. For agent x it takes K_x periods to become skilled, and during this time, he earns no labor income. The distribution of K_x is given by the function $\Gamma(K)$ which is the only source of heterogeneity in this economy, due to credit market imperfections or differences in innate ability. The rest of the setup is unchanged. To simplify the exposition, I assume that $\Gamma(K)$ has no mass points.

I now define a BGP as a situation in which H/L and the skill premium remains constant. In BGP, there is a single-crossing property: if an individual with cost of education K_x chooses schooling, another with $K_{x'} < K_x$ must also acquire skills. Therefore, there exists a cutoff level of talent, $\bar{K}$, such that all $K_x > \bar{K}$ do not get education. Although H/L is in general a complicated function of past education decisions, along BGP it takes the simple form:

$$\frac{H}{L} = \frac{\Gamma(\bar{K})}{1 - \Gamma(\bar{K})}. \tag{17}$$

The agent with talent $\bar{K}$ needs to be indifferent between acquiring skills and not. When he does not acquire any skills, his return at time t is:
$R^{ne} = \int_t^\infty \exp[-(r+\upsilon)(\tau - t)]w_l(\tau)d\tau = w_l \int_0^\infty \exp[-(r+\upsilon-g)\tau]d\tau = w_l(r+\upsilon-g)$ where $r+\upsilon$ is the effective discount rate and I have used the fact that along the BGP wages grow at the rate $g = (\lambda-1)z^*\phi(z^*)$. If in contrast $\bar{K}$ decides to acquire education, he receives nothing for a segment of time of length $\bar{K}$, and receives w_h from then on. Therefore, the return to agent $\bar{K}$ from acquiring education, $R^e(\bar{K})$, can be written as: $R^e(\bar{K}) = \int_{t+\bar{K}}^\infty \exp[-(r+\upsilon)(\tau-t)]w_h(\tau)d\tau = \exp[-(r+\upsilon-g)\bar{K}]w_h/(r+\upsilon-g)$. In BGP, for $\bar{K}$ to be indifferent, we need $R^e(\bar{K}) = R^{ne}$ at all times, so $\omega \equiv w_h/w_l = \exp\left[(r+\upsilon-g)\bar{K}\right]$. Inverting this equation and substituting into (17), we obtain the relative supply of skills as a function of the skill premium:

$$\frac{H}{L} = \frac{\Gamma\left(\ln\omega/\left(r+\upsilon-g\right)\right)}{1-\Gamma\left(\ln\omega/\left(r+\upsilon-g\right)\right)}. \tag{18}$$

A BGP equilibrium with endogenous skill formation is given by the intersection of the relative supply (18) with relative demand for skills given by (15). Ignoring the impact of H/L on g, which is likely to be small, equation (18) defines an upward sloping relative supply relation. When $\eta > 0$, (15) also defines an upward sloping relative demand curve, and multiple BGP equilibria, as drawn in Figure II, are possible. Intuitively, when $\eta > 0$, a higher H/L increases ω, encouraging workers with high K to obtain education and increasing H/L further.

Government policy (e.g. the grant programs or the Vietnam era draft laws) can be thought as reducing the cost of education and shifting the relative supply curve in Figure II to the right (or shifting the function $\Gamma(K)$ to the left). When $\eta > 0$, the return to education ω would also rise, thus raising H/L further. Therefore, the prediction of the model in this case is that subsidies to education lead to an increased tendency to acquire education, and also to a larger education premium due to the directed technology effect. Interestingly, when $\eta > 0$, education subsidies may harm those agents who do not take advantage of the increased incentive to attend college, which is different from the predictions of standard theory where even those who do not take advantage of education subsidies benefit. Also notice that a small exogenous increase in the demand for skills — an increase in γ in equation (2)— increases the skill-premium immediately, encouraging more skill acquisition. This induces the directed technology effect and increases the demand for skills further. If the supply of skills is sufficiently responsive to the skill premium, the exogenous increase in the demand for skills causes a decline in the skill premium before increasing it above its initial value.

A formal analysis of transitory dynamics is more complicated. To simplify the discussion suppose that there is a unique BGP and the supply of skills is not too responsive to the skill premium (i.e. $\Gamma'(K)$ is sufficiently small or the relative supply curve in Figure II is sufficiently steep). Then, it can be shown that in the neighborhood of the BGP, an increase in H/L, due to a decline in the cost of eduction or other reasons, first reduces the skill premium. Then, H/L and Q_h/Q_l increase together, creating both skill-biased technical change and a larger supply of skills. In the case where $\eta > 0$, the economy ends up with higher skill premium, more skill-complementary technologies and more skilled workers (see the Appendix). The process of adjustment is likely to take a long time because technology adjusts slowly (especially in the case where $\phi(.)$ is steeply decreasing). Therefore, the skill premium will rise over time, and earlier generations will be less willing to invest in skills as the returns are far in the future. This pattern of slowly increasing H/L and a gradual shift towards more skill-complementarity technologies is similar to the experience of the United States economy over the past century.

V. The Impact of Trade on Technology

Increased trade with the LDCs where skilled labor is scarce is often suggested as a potential cause of increased wage inequality and contrasted to the explanations based on technology. Since technology has been treated as exogenous in the wage inequality literature, there has been little effort in uncovering the links between these two explanations. This section shows that the direction of technical change is influenced by trade, modifying or qualifying many of the conclusions reached in the previous literature regarding the impact of trade on inequality.

Suppose that the North, where the ratio of skilled to unskilled workers is equal to H^N/L^N, begins trading with an economy, the South, which has a skill ratio $H^S/L^S < H^N/L^N$. There is no endogenous skill accumulation in either economy. What happens to wage inequality in the North? I will answer this question under three different scenarios: (a) no directed technical change; (b) directed technical change and new technologies sold to firms in the South on the same terms as firms in the North; (c) directed technical change and no property rights enforcement in the South. The first scenario is for benchmark, and the truth presumably lies somewhere between (b) and (c), so that there is some sale of technology to the firms in the South, but the enforcement of intellectual property rights is less than perfect. Note that in this model, factor price equalization is guaranteed without further restrictions because each sector employs only one of the non-traded factors (see Ventura [1997] for a similar structure).

A. No Technical Change

Suppose that Q_l and Q_h are given exogenously. Denote the steady state (BGP) skill premium in the North before trade opening by ω^N, and the BGP skill premium after trade opening by ω^W. Also define $\Delta \log \omega = \log \omega^W - \log \omega^N$, $H^W = H^N + H^S$, $L^W = L^N + L^S$ and $H^W/L^W = \hat{\delta} H^N/L^N$, where $\hat{\delta} < 1$ by the fact that the North is more skill intensive than the South (i.e. $\log \hat{\delta} < 0$). Equation (5) from Section II implies:

$$\Delta \log \omega_{NTC} = -\theta \log \hat{\delta} > 0, \tag{19}$$

where the subscript NTC denotes "no technical change" and θ was defined above. Since the South is less skill-intensive, trade with the South increases the relative price of skills, which is the standard effect of trade.

B. Endogenous Technical Change and Full Property Rights

Suppose that A_l and A_h are endogenous as in Section II, and assume that (i) before trade opening, there were no sales of technology to the firms in the South (and no foreign direct investment in the South by firms in the North); and (ii) after trade opening, firms in the South and the North are symmetric and property rights of R&D producers in the North are fully enforced in the South. Trade opening is then equivalent to a decline in the relative supply of skills from H^N/L^N to H^W/L^W. We can now use equation (15) from Section II to obtain the change in BGP skill premium after trade opening:

$$\Delta \log \omega_{PR} = \eta \log \hat{\delta}, \tag{20}$$

where the subscript PR indicates that in this case there is endogenous technical change and property rights of R&D firms are enforced in the South. If $\eta > 0$, contrary to conventional wisdom, trade opening may actually reduce the skill premium for exactly the same reasons that a higher supply of skilled workers increased it in Section II (though as in Proposition 3, trade opening would first increase inequality and then reduce it). More generally, the directed technology effect implies that when intellectual property rights are fully enforced, it is unlikely that international trade increases the skill premium by a large amount.

C. No Intellectual Property Rights in the South

A simple way of modelling the lack of intellectual property rights is to suppose that imitators produce and sell the latest machines invented by R&D firms in the North to firms in the South, so that Northern R&D firms do not receive any revenue from firms in the South. To simplify the analysis, suppose that imitators can produce a machine of quality q at marginal cost $q/(1-\beta)$, so that firms in the South use the same technology as the firms in the North. This specification implies that the market sizes for different machines are unchanged after trade opening. However, there is still an impact on the direction of technical change because the relative price of skill intensive goods changes.

Trade opening first depresses the price of labor intensive goods (i.e. reduces p). However, in the BGP, (10) has to hold in order to equate the return to R&D in skill complementary and labor complementary machines. This implies $p = \left(H^N/L^N\right)^{-\beta}$, so relative prices have to adjust back to their original level to restore equilibrium, and this requires an adjustment in the relative technology of skilled workers away from its original level. In particular, in the new BGP, $Q_h/Q_l = \gamma^{1/(1-\rho)} \left(H^N/L^N\right)^{\beta\rho/(1-\rho)} \hat{\delta}^{-1}$.

The relative wage is now $\omega^W = \gamma^{1/(1-\rho)} \left(H^N/L^N\right)^{\eta} \hat{\delta}^{-1}$, and the change in the skill premium after trade opening is:

$$\Delta \log \omega_{NPR} = -\log \hat{\delta} > 0, \tag{21}$$

where the subscript NPR indicates that there is endogenous technical change but no enforcement of intellectual property rights in the South. The assumption of no intellectual property rights in the South has removed the market size effect completely (the relative market size is still H^N/L^N), but the price effect on the incentives to innovate is present. As noted in Section II, the price effect magnifies the negative effect of the increase in H/L on the skill premium, which explains the large impact of trade on wage inequality.[15] Also, interestingly, trade opening in this case may also increase the skill premium

[15] This argument is related to Wood's [1994] suggestion that trade with the South may have induced "defensive" unskilled labor saving innovations. However, it is not clear what mechanism Wood has in mind since a decline in unskilled wages should normally lead to the introduction of skill-replacing or unskilled labor complementary technologies.

in LDCs, because firms in LDCs use the same technology, and trade opening has induced skill-biased technical change in the North. This contrasts with the prediction of a model with exogenous technology.

In summary, we have: $\Delta \log \omega_{NPR} > \Delta \log \omega_{NTC} > \Delta \log\, \omega_{PR}$ and in fact if $\eta > 0$, $\Delta \log \omega_{PR} < 0$. That is, if property rights are fully enforced in the South, the decline in the relative supply of skills should not lead to a large increase in the skill premium. In contrast, if intellectual property rights are not enforced in the South, simple calculations that ignore the induced change in the direction of technical progress may be seriously underestimating the impact of international trade on inequality.

VI. Concluding Comments

The wages of college graduates and of other skilled workers relative to unskilled labor increased dramatically in the United States over the past fifteen years. To many economists and commentators, this is a direct consequence of the complementarity between skill and new technologies. It is not however clear why new technologies should complement skills. History is full of examples of new technologies designed to save on skilled labor. More generally, inventions and technology adoption are the outcome of a process of choice; as a society, we could have chosen to develop or attempted to develop many different technologies. Therefore, it is necessary to analyze the direction of technical change as well as its magnitude. In its simplest form, this means to pose the question: "why do new technologies complement skills?". This paper suggested that the direction of technical change is determined by the size of the market for different inventions. When there are more skilled workers, the market for technologies that complement skills is larger, hence more of them will be invented, and new technologies will be complementary to skills.

I formalized this observation and discussed its implications. I showed that an exogenous increase in the ratio of skilled workers or a reduction in the cost of acquiring skills could increase wage inequality. The likely path is first a decline, and then a large increase in the skill premium. These observations fit the U.S. facts where the large increase in the ratio of college graduates during the late 1960s and 1970s first depressed the college premium and then increased it to higher levels than before.

The most important area for future work is to develop a test of directed technical change, and its impact on the structure of wages. The testable implication of the model is that after an increase in the supply of college graduates, R&D directed at technologies complementary to college graduates should increase. Although it is difficult in general to determine which technologies are complementary to skilled workers, most economists believe that computers are more complementary to skilled and educated workers than the unskilled. For example, Autor, Katz and Krueger [1997] report that in 1993 only 34.6 percent of high school graduates use computers in contrast to 70.2 percent of college graduates. Moreover, Krueger [1993] shows that controlling for education, workers using a computer obtain a wage premium which suggests that they are more skilled. From the R&D expenditure data reported by the NSF, we see that in 1960 company funded R&D for office computing was 3 percent of the total company funded R&D expenditure. This ratio has increased to 13 percent by 1987,[16] suggesting that during this period of rapid increase in the supply of skills, there has been significantly more R&D directed to one of the technologies most complementary to skills. If other technologies and R&D expenditure can also be classified as complementary to college graduates, the hypothesis of this paper can be tested.

A second area for future research is the application of these ideas to the male-female wage differentials. Since the 1970s, the labor force participation of women has increased substantially and their wages relative to those of male workers have also increased. Part of this change is likely to have been due to reduced discrimination. However, to the extent that male workers use different technologies than female workers, the approach in this paper suggests a new explanation based on directed technical change. The degree to which women use different technologies than men within a plant or sector is probably limited. Nevertheless, women tend to work in different sectors and occupations, and these jobs use different technologies than traditionally male jobs (e.g. desk jobs versus construction). Therefore, it is conceivable that the greater participation of women may have affected the direction of technical change, and via this channel, reduced male-female wage differentials. This hypothesis can be investigated more carefully by studying the relative growth of industries that employ more women, and the relative rate of technical change in these industries.

VII. Appendix

Proof of Proposition 1: (13) uniquely defines Q_h/Q_l for $z_h = z_l$. Then, using (10), (12) and (13) and imposing $z^* = z_h = z_l$ gives equation (14), which uniquely defines z^* because the LHS of (14) is strictly increasing in z^* and the RHS is constant. This establishes that the BGP exists and is uniquely defined. Now substituting for A_h/A_l and

[16] These data come from various issues of Research and Development in Industry Detailed Statistical Tables published by the NSF. I am grateful to Sam Kortum for providing me with these data.

for p, (5) implies $\omega = \gamma^{\frac{1}{1-(1-\beta)\rho}} \left[(Q_h/Q_l)^{\beta\rho} (H/L)^{-(1-\rho)} \right]^{\frac{1}{1-(1-\beta)\rho}}$. Finally, substituting for Q_h/Q_l using (13) gives (15) in the BGP. ∎

Transition Dynamics and Proof of Proposition 2: Equation (10) immediately implies $z_s(j) = z_s$ out of BGP as well as along it. So we only have to determine the time path of z_h, z_l, Q_l and Q_h. (9) holds at all times, so differentiating it with respect to time and using (8), we obtain: $\dot{z}_s = \frac{-\phi(z_s)\dot{V}_s}{\phi'(z_s)V_s} \equiv \frac{\dot{V}_s z_s}{\epsilon_\phi(z_s)V_s}$ for $s = l, h$. I normalize $B \equiv \beta/(1-\beta)$ in this Appendix to simplify the notation. Combining this with (8) and using (9), we obtain:

$$\dot{z}_s = \frac{r + z_s\phi(z_s) - \phi(z_s)p^{1/\beta}N_s}{\epsilon_\phi(z_s)/z_s}. \tag{22}$$

Finally, noting that $\dot{Q}_s/Q_s = (\lambda - 1)\phi(z_s)z_s$ and defining $Q \equiv Q_h/Q_l$, we also have:

$$\dot{Q} = (\lambda - 1)(z_h\phi(z_j) - z_l\phi(z_l)Q. \tag{23}$$

Equations (22) and (23) completely describe the dynamics of the system. To analyze local dynamics and stability in the neighborhood of the BGP, I linearize these equations. Then, around the BGP, $z_l = z_h = z^*, Q = Q^*$, and ignoring constants, we have: $\dot{z}_h = \frac{\sigma(z^*)(z_h - z^*)}{\epsilon_\phi(z^*)/z^*} + \psi_1(z^*, Q^*)(Q - Q^*)$, $\dot{z}_l = \frac{\sigma(z^*)(z_l - z^*)}{\epsilon_\phi(z^*)/z^*} - \psi_2(z^*, Q^*)(Q - Q^*)$ and $\dot{Q} = \sigma(z^*)Q^*(z_h - z_l)$, where $\sigma(z^*) \equiv \phi'(z^*)z^* + \phi(z^*) > 0$. ψ_1 and ψ_2 are analogously defined, and are both positive. The reason why deviations of Q from Q^* affect z_l and z_h differently is that when $Q > Q^*$, p_h is above its BGP value and p_l is below its BGP value. This linearization enables us to reduce the three variable system to two variables: Q and $\zeta \equiv z_h - z_l$. Specifically:

$$\begin{aligned}
\dot{Q} &= \sigma(z^*)Q^*\zeta \\
\dot{\zeta} &= \frac{\sigma(z^*)}{\epsilon_\phi(z^*)/z^*}\zeta + \psi(z^*, Q^*)(Q - Q^*),
\end{aligned}$$

where $\psi(z^*, Q^*) = \psi_1(z^*, Q^*) + \psi_2(z^*, Q^*) > 0$. This linear system has one negative and one positive eigenvalue, and thus a unique saddle path converging to the BGP equilibrium. The rate of convergence to the BGP is $\sqrt{\left(\frac{\sigma(z^*)}{2\epsilon_\phi(z^*)/z^*}\right)^2 + \sigma(z^*)\psi(z^*, Q^*)} - \frac{\sigma(z^*)}{2\epsilon_\phi(z^*)/z^*}$. Thus, when $\sigma(z^*) = \phi'(z^*)z^* + \phi(z^*)$ is lower, or when $\phi(.)$ is more steeply decreasing, convergence is slower. In fact, in the extreme case of $\phi(z) \equiv 1$ (where $\sigma(z^*)$ is at its highest), all our BGP results would be unchanged, but ignoring nonnegativity constraints on consumption, there would be no transitory dynamics. That is, when $Q < Q^*$ we would have $z_l = 0$ and $z_h \to \infty$ for an infinitesimally short while. There would be once again transitory dynamics, however, if nonnegativity constraints on consumption are imposed.

Next, I establish that if $\epsilon_\phi(z)$ is nonincreasing, the system is also globally saddle path stable. Since paths cannot cross and there are no other stationary points of the system, all paths that do not cycle must go to infinity. Therefore, we only have to establish that there are no cycles. Suppose $Q < Q^*$. Note that in this case $p_h H^\beta > p_l L^\beta$. Then consider case (A) where $z_l > z_h$. Then using (22) and the fact that $\epsilon_\phi(z)$ is nonincreasing, $\dot{z}_l/z_l > \dot{z}_h/z_h$, therefore, z_l will remain larger than z_h, and $\dot{Q} < 0$, thus, there cannot be any cycles and all paths go to infinity when $z_l > z_h$. Now consider case (B) where $z_h > z_l$ and $\dot{z}_l/z_l < \dot{z}_h/z_h$. Now $\dot{Q} > 0$, and also as Q increases p_h falls and p_l increases, therefore from , it will always be the case that $\dot{z}_l/z_l < \dot{z}_h/z_h$. Hence, in this case too, cycles are not possible. Now consider case (C) where $z_h > z_l$ and $\dot{z}_l/z_l > \dot{z}_h/z_h$. If as $t \to \infty$, $z_h > z_l$ and $\dot{z}_l/z_l > \dot{z}_h/z_h$, then we converge to $z_h = z_l = z^*$ and $Q = Q^*$, and we know there is a unique saddle path locally and paths cannot cross, therefore, we must be on that path. Instead if $z_h = z_l$ at some point where $Q \neq Q^*$, then once again cycles can be ruled out. We must have either that $z_h > z_l$ and $Q > Q^*$ which puts us in case (A), and cycles are not possible and all paths go to infinity. Or, it could be the case that $z_h > z_l$ and $Q > Q^*$, which, by the analogous argument to case (A), again rules out cycles. Thus, there must be a unique saddle path from all points $Q < Q^*$. The proof for the case of $Q > Q^*$ is analogous. ■

Proof of Proposition 3: Take Q_h/Q_l as given. Then, given optimal monopoly pricing and profit maximization by firms, we have:
$A_h/A_l = (Q_h/Q_l)\, p^{(1-\beta)/\beta} \,(H/L)^{(1-\beta)}$. Now substituting for p_h and p_l and rearranging:

$$\frac{A_h}{A_l} = \left[\gamma^{(1-\beta)/\beta}\left(\frac{Q_h}{Q_l}\right)\left(\frac{H}{L}\right)^{(1-\beta)\rho}\right]^{\beta/(1-(1-\beta)\rho)}.$$

Substituting into (5), we obtain:

$$\omega = \gamma^{1/(1-(1-\beta)\rho)}\left(\frac{Q_h}{Q_l}\right)^{\beta\rho/(1-(1-\beta)\rho)}\left(\frac{H}{L}\right)^{-\theta},$$

where $\theta \equiv (1-\rho)/(1-(1-\beta)\rho)$ as defined in the text. Therefore, at given technology (i.e. given Q_h/Q_l), $\Delta \log \omega = -\theta \log \delta$. Once technology adjusts to its new BGP level, we have the result of Proposition 1, thus $\Delta \log \omega = \eta \log \delta$. ■

Details of the Model of Section III: The demands for sector h machines now come from firms employing high ability college graduates and high ability high school graduates, and vice versa for sector l machines. These demand curves have the same elasticity as in the text, thus the optimal pricing policy is the same. Therefore, the free-entry condition for sector h machines, analogous to (10), can be written as:

$$\frac{\beta}{(1-\beta)B}\phi(z_h)\left[p_{hh}^{1/\beta}\mu_h H + p_{lh}^{1/\beta}\mu_l L\right] = r + z_h\phi(z_h), \tag{24}$$

and similarly for z_l, where p_{hh} is the price of the intermediate good produced by high ability college graduates in terms of the final good, p_{lh} is for high ability high school graduates, etc. Then, using competitive pricing and the definition of A_{hh}: $p_{hh}^{1/\beta} = (1-\beta)^{(1-2\beta)\nu/\beta} Q_h^{-(1-\rho)\nu} (\mu_h H)^{-(1-\rho)\nu} Y^{(1-\rho)\nu}$ where $\nu \equiv -(1-(1-\beta)\rho)^{-1}$and p_{lh}, p_{hl} and p_{ll} are similarly defined. Substituting these into (24) and simplifying, we obtain (16) in the text.

Finally, consider residual wage inequality among college graduates:

$$\omega^h \equiv \frac{w_{hh}}{w_{hl}} = \left(\frac{A_{hh}}{A_{hl}}\right)^{\rho}\left(\frac{\mu_h H}{(1-\mu_h)H}\right)^{-(1-\beta\rho)}.$$

Substituting for A_{hh} and A_{lh} gives the expression in the text. ω^l is derived similarly ■

Transitory Dynamics with Endogenous Skills: I focus on the case of interest, which has $\eta > 0$. Linearizing around a BGP, $\dot{Q}$ still only depends on ζ. Thus, ignoring constants, $\dot{Q} = a_{21}\zeta$ where $a_{21} > 0$. In contrast, $\dot{\zeta} = a_{11}\zeta + a_{12}Q - a_{13}(H/L)$ where all coefficients are positive. This is because z_s depends on V_s which is an increasing function of Q_s and decreasing in N_s. Finally, around the BGP, we have that $\dot{H} \approx -\upsilon H + \Gamma\left(\log\omega/[r+\upsilon-g]\right)$, and similarly for $\dot{L}$. Therefore, the rate of change of H/L is a decreasing function of H/L and an increasing function of the relative wage ω, which is itself decreasing in H/L and increasing in Q_h/Q_l. Thus, in the neighborhood of the BGP the linearized differential equation is: $\dot{\left(H/L\right)} = a_{32}Q - a_{33}(H/L)$ where once again the coefficients are positive. Note that a_{32} is the response of the supply of skills to the skill premium, so it is smaller when $\Gamma'(K)$ is lower, that is when education choices are not very responsive to wages. Therefore, around the BGP, this system has two state variables and one control variable. Thus, for well-behaved transition dynamics, the linearized differential equation system needs to have two negative (x_1, x_2) and one positive eigenvalues (x_3). Standard arguments establish that: $x_1x_2x_3 = a_{21}\left(a_{12}a_{33} - a_{13}a_{32}\right)$. So when a_{32} is sufficiently small —so that education choices are not too responsive—, either all roots are positive or two of them are negative. Also, $x_1x_2 + x_1x_3 + x_2x_3 = -(a_{11}a_{33} + a_{12}a_{21}) < 0$, which implies that all roots cannot be positive. So, as long as education is not too responsive to the skill premium, the system is saddle path stable around the BGP. Therefore, when H/L and Q_h/Q_l are below their BGP value, we have $z_h > z_l$ and the economy converges to BGP by accumulating skills and more skill-complementary technologies. ■

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