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Patterns of Skill Premia

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This paper develops a model to analyse how skill premia differ over time and across countries, and uses this model to study the impact of international trade on wage inequality. Skill premia are determined by technology, the relative supply of skills, and trade. Technology is itself endogenous, and responds to profit incentives. An increase in the relative supply of skills, holding technology constant, reduces the skill premium. But an increase in the supply of skills over time also induces a change in technology, increasing the demand for skills. The most important result of the paper is that increased international trade induces skill-biased technical change. As a result, trade opening can cause a rise in inequality both in the U.S. and the less developed countries, and thanks to the induced skill-biased technical change, this can happen without a rise in the relative prices of skill-intensive goods in the U.S., which is the usual intervening mechanism in the standard trade models.

1. INTRODUCTION

This paper develops a tractable model linking skill premia (returns to skills) to relative supplies, technology, and trade. The main innovation of the model is to treat the degree of skill bias of technology, and hence the demand for skills, as endogenous, and relate it to the supply of skills and to international trade. I show that this framework is broadly consistent with the time-series evidence on the evolution of the relative supplies and the skill premium in the U.S., and cross-country differences in skill premia. It also suggests that increased international trade could be a major cause of the increase in wage inequality because it *induces skill-biased technical change*.

The literature on wage inequality is now vast. Figure 1 shows, a number of U.S. facts pertinent to this literature (see Appendix A for details). Starting in 1979, the college premium—the wages of college graduates relative to the wages of high school graduates—increased rapidly to a level unprecedented in the post-war period. Moreover, this happened while the supply of college skills was rising rapidly. The implication is that the demand for skills must have expanded even more sharply during this time period. The literature has drawn a sharp distinction between two possible causes for the increase in the demand for skills: skill-biased technical change and increased international trade.[1]

The trade explanation suggests that the U.S. skill premium increased because trade with skill-scarce less developed countries (LDCs) raised the demand for skilled Americans. In fact, between the early 1970's and mid-1990's the share of imports from LDCs in the U.S. GDP increased by over fourfold. Although the trade explanation is theoretically plausible, most economists discount the role of international trade for a variety of reasons.

First, international trade should increase the relative price of skill-intensive goods and raise the "derived" demand for skills via this channel. However, most evidence points to a declining or constant relative price of skill-intensive goods over this period (see, for example, Lawrence and Slaughter (1993), Sachs and Shatz (1994), Desjounqueres, Machin and Van Reenen (1999)).

1. Throughout I use the term skill-biased technical change to mean any change in technology that increases the aggregate demand for skills. Accordingly, an increase in the overall productivity of a sector that uses skilled workers more intensively may correspond to skill-biased technical change depending on the elasticities of substitution.

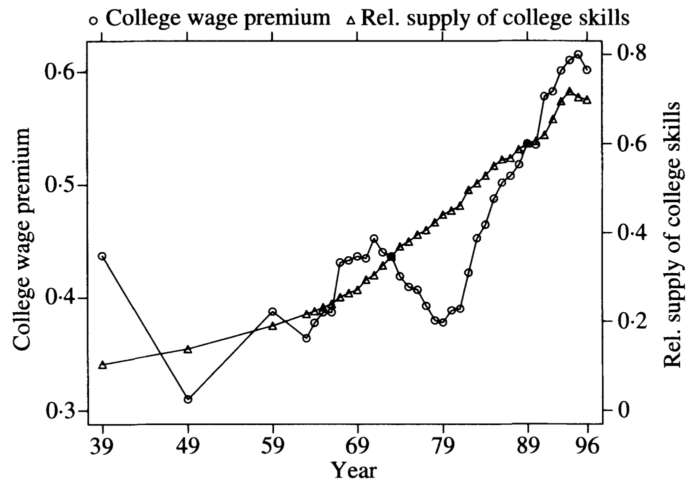

FIGURE 1

The behaviour of the (log) college premium and relative supply of college skills (weeks worked by college equivalents divided by weeks worked by noncollege equivalents) in the U.S. between 1939 and 1996

Second, as Figure 1 shows the skill premium rose despite steadily increasing relative supply of skills for the whole post-war period. This pattern suggests that there has been secular skill-biased technical change, increasing the demand for skills for most of this period. Many economists then find it more plausible that skill-biased technical change is also responsible for the more rapid increase in the demand for skills over the recent decades (*e.g.* Autor, Katz and Krueger, 1998). The fact that all sectors, even those producing less skilled goods, increased their demands for more educated workers over this time period also suggests that skill-biased technical change played a more important role than trade. Third, if trade were the cause of the increase in inequality in the U.S., inequality should have fallen in the LDCs that have started trading with the more skill-abundant U.S. economy. The evidence, however, suggests that more of the LDCs experienced rising inequality after opening to international trade (see the discussion presented in Section 2). Finally, a number of economists have pointed out that the U.S. trade with the LDCs is not important enough to have a major impact on the U.S. product market prices and consequently on wages.[2]

The most important hypothesis in this paper is that increased international trade may have been more important than generally believed because it induces skill-biased technical change. Therefore, this paper argues that the two competing explanations for the increase in the demand for skills, trade and technology, may be related. The basic reason why trade induces skill-biased technical change is that it creates a tendency for the U.S. relative price of skill-intensive goods to increase. This change in relative prices increases the demand for technologies used in the production of these goods, makes these technologies more profitable to develop, and encourages further technical change directed at them.

The theory proposed in this paper avoids the main criticisms levelled against explanations that view trade as the major cause of the recent rise in U.S. wage inequality. Because trade induces skill-biased technical change, the explanation offered here is consistent with the importance of skill-biased technical change documented by other studies and points out that

2. See, for example, Katz and Murphy (1992), Berman, Bound and Griliches (1994), Krugman (1995) and Borjas, Freeman and Katz (1997), but also the critique by Leamer (1994, 1996).

standard calculations underestimate the impact of trade on wage inequality. Furthermore, with sufficiently pronounced skill-biased change, the demand for skills and inequality can increase in the LDCs also. Finally, although it is the increase in the relative price of skill-intensive goods that encourages skill-biased technical change, the increased productivity of skilled workers both in the U.S. and in other countries may eventually return the relative price of skill-intensive goods to its original (pre-trade) level in the U.S. So existing evidence on the changes in the U.S. relative price of skill-intensive goods does not refute trade-based explanations of the increase in U.S. wage inequality.

The related literature includes models of the increase in inequality in the U.S., such as Galor and Tsiddon (1997), Greenwood and Yorukoglu (1997), Acemoglu (1999*a*), Caselli (1999), Aghion, Howitt and Violante (2000), Krusell, Ohanian, Rios-Rull and Violante (2000) and Galor and Maov (2000). Acemoglu (1998) is most closely related. In that paper, I constructed a similar model of directed technical change to show that the increase in the number of college graduates during the 1960's and 1970's in the U.S. can explain both the decline in the college premium during the 1970's and its sharp rise during the 1980's. Here, I extend that model in a number of directions. First, in Acemoglu (1998), I considered a closed economy model, while here I analyse a multicountry set-up, where the equilibrium skill bias of technology is determined at the world level. This analysis highlights how the relationship in the time series and the cross section between the supply of skills and skill premia is shaped by different factors. Second and most important, I incorporate the analysis of international trade into this framework, and show that trade opening induces skill-biased technical change.

Previous studies, including among others Kennedy (1964), Drandakis and Phelps (1965), Samuelson (1965), Ahmad (1966), Hayami and Ruttan (1970) and David (1975), discuss the concept of induced innovations, which is closely related to directed technical change, but these papers do not have a micro-founded model of technological change, and do not focus on the determinants of skill premia. The analysis here also obviously borrows from the endogenous growth literature (for example, Romer (1990), Grossman and Helpman (1991*a*,*b*), Aghion and Howitt (1992, 1998)), but technical change here is not only endogenous, but also *directed*, in the sense that the degree of skill bias of new technologies responds to profit incentives.

Finally, previous contributions that emphasize the importance of trade on inequality include Leamer (1992, 1994), Wood (1994), Baldwin (1995), Borjas and Ramey (1995) and Baldwin and Cain (1997) and the papers in Bhagwati and Kosters (1994). The potential impact of trade on technology was first raised by Wood (1994) who argued that trade with the LDCs will lead to *defensive skill-biased innovations*. Wood, however, did not develop the mechanism through which such defensive innovations could occur.[3]

The plan of the paper is as follows. In the next section, I analyse the effect of international trade on skill premia with exogenous technology. In Section 3, I introduce a model of endogenous (directed) technical change where skill- and labour-complementary technologies can be developed at different rates, and show that this model is consistent with a number of salient features of time-series and cross-country evidence on skill premia. In Section 4, I develop the argument that trade opening can cause skill-biased technical change in the U.S., and show that the increase in international trade could be the driving force of the rise in inequality over the past several decades. Section 5 concludes with some future directions and extensions. In particular,

3. Haskel and Slaughter (1999) investigate whether trade led to faster technological progress and affected the wage structure through this channel in the U.K. More recent works by Epifani and Ganica (2002) and Thoenig and Verdier (2002) provide additional mechanisms for international trade to affect the skill bias of world technology, while Xu (2001) extends the analysis in my paper to an economy where both sectors employ both factors. Zeira (2001) also discusses the implications of trade and technology on inequality in a unified framework, but does not model the impact of trade on technology.

I analyse the effect of trade on technologies chosen by another set of technological leaders, such as the European economies, and show how trade may lead to skill-biased technical change in the U.S., but labour-biased technical change in Europe. I also analyse how international trade may affect technology adoption in LDCs.

2. TRADE AND SKILL PREMIA

I begin with a simple model that illustrates the effect of international trade on skill premia in the standard (Heckscher–Ohlin) trade model. I will then use this framework to endogenize technology, and investigate the effect of relative supplies on technology and the interaction between trade and technology.

Consider a world economy consisting of $J+1$ countries, the U.S., and J LDCs. H denotes skilled workers and L denotes unskilled workers. I assume that the U.S. has a higher fraction of skilled workers than the LDCs, that is, $H^U/L^U > H^j/L^j$ for $j = 1, \dots, J$, where U denotes the U.S. and j denotes the j-th LDC. I will sometimes denote the U.S. with $j = 0$ to simplify the notation. For now, I take the relative supplies of skills as given. In the Appendix, I show that all the results in the paper generalize when these supplies are endogenized.

All consumers in all countries have identical preferences:

$$U(t) \equiv \int_t^\infty \exp(-r(\tau - t))C(\tau)d\tau, \tag{1}$$

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

Consumption (utility) is defined over a constant elasticity of substitution (CES) aggregate of a skill-intensive and a labour-intensive good. More specifically, in country j, we have aggregate consumption as

$$C^j = [\gamma(C_l^j)^{\frac{\varepsilon-1}{\varepsilon}} + (1-\gamma)(C_h^j)^{\frac{\varepsilon-1}{\varepsilon}}]^{\frac{\varepsilon}{\varepsilon-1}}, \tag{2}$$

where C_l^j is the total consumption of the labour-intensive good, C_h^j is the total consumption of the skill-intensive good, and $\varepsilon \in [0, \infty)$ is the elasticity of substitution between the two goods. I denote the prices of the two final goods in country j by p_l^j and p_h^j. The market for these goods is competitive, so market clearing implies that the relative price of the skill-intensive good in country j is

$$p^j \equiv \frac{p_h^j}{p_l^j} = \frac{1-\gamma}{\gamma}\left(\frac{C_h^j}{C_l^j}\right)^{-\frac{1}{\varepsilon}}. \tag{3}$$

This relative price will differ across countries when there is no international trade.

I assume that the labour-intensive good is produced using unskilled workers, while the skill-intensive good is produced using skilled workers only.[4] In particular, let the production of these two goods in country j be

$$Y_h^j = A_h^j H^j \qquad \text{and} \qquad Y_l^j = A_l^j L^j, \tag{4}$$

where A_h^j is the productivity of skilled workers in country j, and A_l^j is defined similarly. In the absence of international trade, domestic consumption must equal domestic production, that is

4. Xu (2001) generalizes the results in this paper to the case where both goods employ both factors. His results are relevant for the debate on whether the sector or factor bias of technical change matters more for wage inequality in an open economy, see for example Haskel and Slaughter (1998).

$C_s^j = Y_s^j$ for $s = l, h$ and all j. So the relative price of the skill-intensive good in country j will be

$$p^j = \frac{1-\gamma}{\gamma}\left(\frac{A_h^j H^j}{A_l^j L^j}\right)^{-\frac{1}{\varepsilon}}. \tag{5}$$

Normalizing the price of the final good in each country to 1, we also have

$$[\gamma^{\varepsilon}(p_l^j)^{1-\varepsilon} + (1-\gamma)^{\varepsilon}(p_h^j)^{1-\varepsilon}]^{\frac{1}{1-\varepsilon}} = 1. \tag{6}$$

Labour markets are competitive, so skilled and unskilled workers in each country will be paid their marginal products. Therefore, the skill premium—the wages of skilled workers divided by the wages of unskilled workers—in country j is[5]

$$\omega^j = \frac{w_h^j}{w_l^j} = p^j \frac{A_h^j}{A_l^j} = \frac{1-\gamma}{\gamma}\left(\frac{A_h^j}{A_l^j}\right)^{\frac{\varepsilon-1}{\varepsilon}}\left(\frac{H^j}{L^j}\right)^{-\frac{1}{\varepsilon}}. \tag{7}$$

This equation highlights the main forces affecting skill premia in a closed economy. For *given skill bias of technology*, as captured by A_h^j/A_l^j, the relative demand curve for skill is downward sloping with elasticity ε, as shown by the curve denoted CT in Figure 2. An increase in H^j/L^j creates a substitution of skilled workers for unskilled workers (or of the skilled good for the unskilled good), and reduces the relative earnings of skilled workers. The effect of a change in A_h^j/A_l^j is more complex, and depends on the elasticity of substitution. If the elasticity of substitution, ε, is greater than 1, then $\frac{\partial \omega}{\partial A_h/A_l} > 0$, and improvements in the skill-complementary technology increase the skill premium. The converse is obtained when $\varepsilon < 1$: an improvement in the productivity of skilled workers, A_h^j, relative to the productivity of unskilled workers, A_l^j, reduces the skill premium. The conventional wisdom is that the skill premium increases when skilled workers become relatively more—not relatively less—productive, which is consistent with $\varepsilon > 1$. Almost all estimates show an elasticity of substitution between skilled and unskilled workers greater than 1 (see, for example, Freeman, 1986). So in the rest of the paper I take ε to be greater than 1.

Suppose that all countries start trading internationally without any trading costs or thick borders. Free trade implies that there will be a unique world relative price of skill-intensive goods, $\hat{p}$, and given this price, all consumers will choose the same consumption ratio of skill intensive goods to labour-intensive goods, C_h^j/C_l^j. Therefore, the world equilibrium relative price is given by

$$\hat{p} = \frac{1-\gamma}{\gamma}\left[\frac{\sum_{j=0}^{J} A_h^j H^j}{\sum_{j=0}^{J} A_l^j L^j}\right]^{-\frac{1}{\varepsilon}}, \tag{8}$$

where recall that country $j = 0$ stands for the U.S. Since labour markets continue to reward workers according to marginal product, the skill premium in country j becomes

$$\hat{\omega}^j = \hat{p}\frac{A_h^j}{A_l^j}. \tag{9}$$

This expression differs from (7) since the relative price of skill-intensive goods is not indexed by j. This is because international trade equates goods prices. However, trade does not necessarily

5. Equation (7) may imply a negative skill premium, *i.e.* $\omega^j < 1$, in which case skilled workers would prefer to work as unskilled workers (and perhaps be more productive at these tasks than unskilled workers themselves, receiving a positive skill premium). Throughout the paper, I assume that H^j/L^j is such that the skill premium is always positive (see footnote 16).

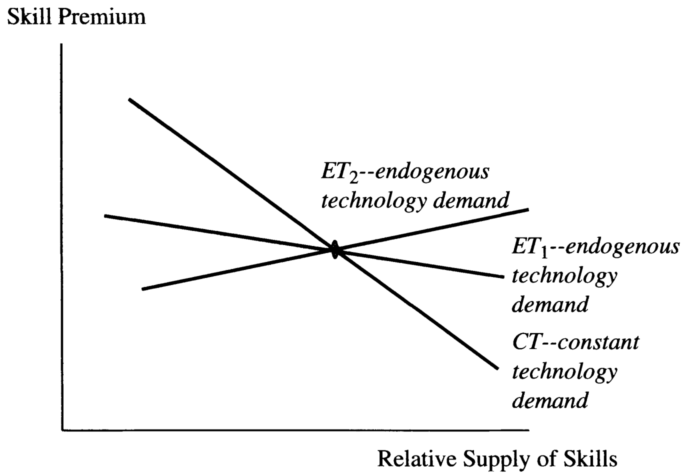

FIGURE 2
Relative demand for skills

imply factor price equalization, or even skill premium equalization, because countries differ in their technologies (Trefler, 1993). Moreover, trade with the skill-scarce LDCs does not necessarily lead to an increase in the U.S. skill premium. Comparing the skill premium in the U.S. after trade opening given by (9), $\hat{\omega}^{US} = \hat{p} A_h^U / A_l^U$, to that implied by equation (7), $\omega^{US} = p^j A_h^U / A_l^U$, we find that trade increases the skill premium in the U.S. if and only if the post-trade relative price of skill-intensive goods is greater than the pre-trade relative price in the U.S. Although $H^U/L^U > H^j/L^j$ for all $j \geq 1$, if A_h^U/A_l^U were sufficiently smaller than A_h^j/A_l^j's, the world supply of skill-intensive goods could be greater than that in the U.S., and U.S. wage inequality could fall as a result of trade opening. Nevertheless, this scenario appears implausible; if anything, the U.S. may be expected to be relatively more productive in the production of skill-intensive goods which employ more advanced techniques. Therefore, for our purposes, we can take the following benchmark:

$$A_s^j = \theta^j A_s^U \qquad \text{for all } j \text{ and } s = l, h \tag{10}$$

with $\theta^j \leq 1$ for all j. Equation (10) implies that other countries may be less productive than the U.S., but they will be so proportionately in all goods. In the concluding section, I discuss how θ^j's may be determined endogenously from profit incentives in the LDCs.

Using the assumption in (10), we have

$$\hat{p} = \frac{1-\gamma}{\gamma}\left[\frac{A_h}{A_l}\left(\frac{H^W}{L^W}\right)\right]^{-\frac{1}{\varepsilon}} > p^U = \frac{1-\gamma}{\gamma}\left[\frac{A_h H^U}{A_l L^U}\right]^{-\frac{1}{\varepsilon}}, \tag{11}$$

where $H^W \equiv H^U + \sum_{j=1}^J \theta^j H^j$ is the world "effective" supply of skilled workers and $L^W \equiv L^U + \sum_{j=1}^J \theta^j L^j$ is the world "effective" supply of unskilled workers. The θ^j terms are here to take account of the fact that LDC workers may be using less productive technologies. The result that $\hat{p} > p^U$ follows from the assumption that $H^U/L^U > H^j/L^j$ for all j, which ensures $H^U/L^U > H^W/L^W$. In fact, throughout the paper I will adopt the slightly stronger assumption that

$$H^W/L^W > H^j/L^j \qquad \text{for all } j > 0, \tag{12}$$

which ensures that the world economy after trade opening will be more skill intensive than each LDC, so that $\hat{p} < p^j$ for all j.

Now from (9), the post-trade skill premium in all countries is

$$\hat{\omega} = \hat{p}\left(\frac{A_h}{A_l}\right) > \omega^U, \tag{13}$$

where the fact that the world skill premium, $\hat{\omega}$, is greater than the pre-trade U.S. skill premium, ω^U, is a direct consequence of (11). Therefore, trade between the skill-abundant U.S. and skill-scarce LDCs increases the demand for, and the price of, skill-intensive goods produced in the U.S. Via this channel, trade increases the (derived) demand for the services of American skilled workers, raising the U.S. skill premium.

Although this analysis shows that increased international trade could be responsible for the rise in skill premia and inequality in the U.S., most economists discount the role of trade for the reasons discussed briefly in the introduction. First, as equation (13) shows, the effect of international trade works through a *unique intervening mechanism*: free trade with the LDCs increases the relative price of skill-intensive goods, p, and affects the skill premium via this channel. Perhaps the most damaging piece of evidence for the trade hypothesis is that most studies suggest the relative price of skill-intensive goods did not increase over the period of increasing inequality. Lawrence and Slaughter (1993) found that during the 1980's the relative price of skill-intensive goods actually fell. Sachs and Shatz (1994) found no major change or a slight decline, while a more recent paper by Krueger (1997) found an increase in the relative price of skill-intensive goods, but only for the 1989–1995 period. More recent work by Desjounqueres *et al.* (1999) presents evidence showing no increase or even a decline in the relative price of skill-intensive goods in the U.K., Germany, Japan, Denmark and Sweden, and a small increase in the U.S. between 1974 and 1989, while Haskel and Slaughter (1999) show an increase using U.K. data.

Second, a variety of evidence suggests that skill-biased technical change has been important in the changes in the wage structure. For example, Figure 1 shows that there has been steady skill-biased technical change throughout the past 60 years, and Berman *et al.* (1994), Autor *et al.* (1998), Berman, Bound and Machin (1998) and Machin and Van Reenen (1998) document that skill-biased technical change may have been faster during the past 25 years. Moreover, these authors show that all sectors, even those producing less skill-intensive goods, increased their demands for more educated workers. This pattern is consistent with the importance of skill-biased technical change, but not with an increase in the demand for skills driven mainly by increased international trade.

Third, a direct implication of the trade view is that, while demand for skills and inequality increase in the U.S., the converse should happen in the LDCs that have started trading with the more skill-abundant U.S. economy. The evidence, however, suggests that more of the LDCs experienced rising inequality after opening to international trade. Although the increase in inequality in a number of cases may have been due to concurrent political and economic reforms, the preponderance of evidence is not favourable to this basic implication of the trade hypothesis.[6]

6. Hanson and Harrison (1994) show that the skilled–unskilled wage gap in Mexico increased during the 1980's despite substantial trade opening. Duryea and Szekely (2000) and Behrman, Birdsall and Szekely (2001) find that between the early 1980's and mid-1990's, wage inequality increased in Brazil, Mexico, Venezuela, Argentina and Bolivia, and remained approximately constant in Chile and Costa Rica, despite substantial global trade opening during this time period. Robbins (1995) finds a sharp increase in the relative demand for skills in Argentina, Chile, Costa Rica, Mexico, the Philippines, Taiwan and Uruguay while these economies were opening to trade. Desjounqueres *et al.* (1999) report increasing wage differentials between nonproduction and production workers in Chile and Pakistan, no change in India and Brazil, and a decline in Colombia, but an increase in the demand for skills in all the cases. Davis (1992) reports declining wage inequality in South Korea, Venezuela and Colombia, and a slight increase in Brazil during the 1980's.

Finally, a number of economists have pointed out that U.S. trade with the LDCs is not important enough to have a major impact on the U.S. product market prices and consequently on wages. Krugman (1995) illustrates this point by undertaking a calibration of a simple North–South model. Katz and Murphy (1992), Berman *et al.* (1994) and Borjas *et al.* (1997) emphasize the same point by showing that the content of unskilled labour embedded in U.S. imports is small relative to the changes in the supply of skills taking place during this period.

Although many of the assumptions that go into these factor-content calculations can be questioned, it is useful to briefly consider the relevant magnitudes to compare them later to the implications of the theory developed here. The simple model in this section suggests that to estimate the percentage (log point) change in the skill premium, we only need to know the percentage (log point) difference between H^U/L^U and H^W/L^W. In particular, equations (11) and (13) immediately imply that

$$\ln \hat{\omega} - \ln \omega^U = -\frac{1}{\varepsilon}\left[\ln\left(\frac{H^W}{L^W}\right) - \ln\left(\frac{H^U}{L^U}\right)\right].$$

In practice, there exist trade barriers even after trade opening, so H^W/L^W does not correspond to the actual ratio of skilled to unskilled workers in the world economy. The literature has attempted to deal with this problem by estimating the factor content of trade with the LDCs. Even though, as pointed out by Leamer (1994, 1996), there may be conceptual problems with such factor content studies, they are theoretically correct within the context of the simple model considered here, so I will make use of these calculations to quantify the possible impact of trade.[7]

Borjas *et al.* (1997) present a number of alternative estimates of the increase in the unskilled labour content of trade with LDCs between 1980 and 1995. The most appealing of these is what they refer to as the "high" estimate. This estimate assumes that in the absence of the increase in imports from the LDCs, domestic production would have replaced these imports, using average industry skill shares and labour productivity from 1970 (*i.e.* before the growth of manufacturing imports from the LDCs). This counterfactual is plausible, in part, because imports typically dislocate the less efficient and more labour-intensive establishments. The numbers that Borjas *et al.* (1997) report using this assumption, and taking 1980 as the pre-trade and 1995 as the post-trade period, imply that $\ln(H^W/L^W) - \ln(H^U/L^U) \approx 0{\cdot}04$. To translate this into a change in skill premium, we also need an estimate of ε. The typical elasticity used in this literature is $\varepsilon = 1{\cdot}4$ which is estimated from time-series variation. The only estimate using a quasi-exogenous variation comes from Angrist (1995), who exploits the increase in the supply of college graduates in the West Bank and Gaza Strip during the 1980's. The elasticity implied by Angrist's (1995) estimates is over $\varepsilon = 2$, which is also consistent with the results of Card and Lemieux (2001). When $\varepsilon = 1{\cdot}4$, these numbers imply that international trade will have led to an approximately 3% increase in the skill premium ($0{\cdot}04/1{\cdot}4 \approx 0{\cdot}03$), while $\varepsilon = 2$ puts the same number at 2% ($0{\cdot}04/2 \approx 0{\cdot}02$).[8] Over this time period, the actual change in the college premium was just under 20%, so international trade is unlikely to account for more than 10–15% of the actual change (2–3% of the 20% actual increase). Although this is a nontrivial amount, it leaves the bulk of the increase unexplained, and underlies the conclusion of many studies that international trade has played a relatively minor role in the increase in inequality.

While the above arguments suggest that increased international trade with the LDCs is not the major cause of the changes in the wage structure by itself, they do not rule out a powerful effect of international trade when it interacts with technical change: in a world with endogenous

7. More generally, this factor-content approach is correct when countries are in a diversified equilibrium both before and after trade opening, see Dearoff and Staiger (1988).

8. Using a different methodology Krugman (1995) calculates the same number to be 3·7%.

technical change, increased international trade could affect technology choice, and have a large effect through this channel. This is the issue I turn to next.

3. ENDOGENOUS TECHNOLOGY

3.1. *Endogenous technology without international trade*

In this section, I introduce the baseline endogenous (directed) technical change model, which draws on my previous work, Acemoglu (1998). I start with the case in which there is no international trade in commodities.

I modify the production functions given in (4) to endogenize A_h^j and A_l^j. Specifically,

$$Y_l^j = \int_0^1 \tilde{q}_l^j(i)^\beta x_l^j(i)^{1-\beta}(L^j)^\beta di \qquad \text{and} \qquad Y_h^j = \int_0^1 \tilde{q}_h^j(i)^\beta x_h^j(i)^{1-\beta}(H^j)^\beta di. \tag{14}$$

This formulation implies that there is a continuum of (different types of) machines or intermediates, $x_l^j(i)$'s, used by unskilled workers and a different set, $x_h^j(i)$'s, used by skilled workers. Here $x_s^j(i)$ denotes the quantity of machine type i used with workers of skill type s in country j, while $\tilde{q}_s^j(i)$ denotes quality ("productivity" of the machine being used). To model the skill bias of technology, it is essential to have two different types of machines, one type complementing skilled workers more than the unskilled. Having a range of machines, rather than only one for each skill type, simplifies the analysis by making technical progress non-stochastic and continuous. The assumption that none of the machines are used by both types of workers is only for simplicity.

The production functions in (14) exhibit constant returns to scale in variable factors: if labour and the quantities of all machines, the $x_s^j(i)$'s, are doubled, output will be doubled. Despite constant returns to scale at the firm level, the aggregate production possibilities set of the economy will exhibit increasing returns to scale because technologies, the $\tilde{q}_s^j(i)$'s, will also be determined endogenously.

Producers in country j can use the machines developed locally or can adopt machines developed in another country, j'. But in this latter case, because these machines may not be "appropriate" to their needs,[9] their productivity is lower than the productivity of producers in the country of origin by a factor $(1-\theta^j) \leq 0$. Whether θ^j is strictly less than 1 or not is not essential for the results. Mathematically, we have

$$\tilde{q}_s^j(i) = \begin{cases} q_s^j(i) & \text{or} \\ \theta^j q_s^{j'} & \text{if } j \neq j', \end{cases}$$

where recall that $\tilde{q}_s^j(i)$'s denote the productivity of machines *used* in country j, and $q_s^j(i)$'s are the productivity of the most advanced machine *developed* in country j.

9. There are many possible reasons for this inappropriateness of technology. Countries require crops suitable for their own climate, vaccines that deal with the prevalent diseases in their region, and technologies that exploit their existing know-how. So technologies developed in the U.S. may be partly "inappropriate" to different environments, and hence less productive when used in other countries. Atkinson and Stiglitz (1969), Stewart (1977), Basu and Weil (1998) and Acemoglu and Zilibotti (2001) emphasize the importance of "appropriateness" of technologies in the context of economic development.

I denote the rental price of machine i for skill type s in country j of quality $\tilde{q}_s^j(i)$ by $\chi_s^j(\tilde{q}_s^j(i))$. Equation (14) implies that machine demands, as functions of machine qualities, are

$$x_l^j(\tilde{q}_l^j(i)) = \left[\frac{(1-\beta)p_l^j}{\chi_l^j(\tilde{q}_l^j(i))}\right]^{1/\beta} \tilde{q}_l^j(i)L^j \quad \text{and} \quad x_h^j(\tilde{q}_h^j(i)) = \left[\frac{(1-\beta)p_h^j}{\chi_h^j(\tilde{q}_h^j(i))}\right]^{1/\beta} \tilde{q}_h^j(i)H^j. \tag{15}$$

Product prices, p_s^j, are indexed by j, because, in the absence of international trade, they will vary across countries.

The R&D process is modelled as in Grossman and Helpman (1991*a*,*b*) and Aghion and Howitt (1992): an innovation based on a machine of quality q creates a new vintage with quality λq where $\lambda > 1$. One unit of the final good spent in R&D for a machine of quality q leads to an innovation at the flow rate $z\phi(z)$, where z is the aggregate research effort devoted to the discovery of this machine. Research effort z on a machine of quality q costs Bqz units of the final good. This formulation implies that more advanced machines are more expensive to discover. I assume that $\phi'(\cdot) \leq 0$, which implies that greater research effort runs into decreasing returns within a given period (there are constant returns to scale when $\phi'(\cdot) = 0$). But throughout $z\phi(z)$ is strictly increasing in z, so that greater research effort always leads to faster innovation. Also, without loss of any generality, I normalize $B \equiv \beta(1-\beta)\lambda$, which will simplify the notation below.

I will focus on the case in which patents are always perfectly enforced in the U.S., but may not be enforced in LDCs. The inventor of a new machine obtains a U.S. patent, and becomes the monopolist supplier of this technology. Since the demands for machines implied by equations (15) are iso-elastic, the profit-maximizing monopoly price for these machines is a constant markup over marginal cost. I assume $\lambda > (1-\beta)^{-(1-\beta)/\beta}$, which ensures that R&D firms in the U.S. will set this monopoly price (rather than a limit price making final good firms indifferent between buying the two latest vintages). R&D firms in country j can only undertake innovations on technology q^j. Finally, I assume that machines depreciate fully after use,[10] and the marginal cost of producing a machine is constant, irrespective of quality. Without loss of any generality, I normalize this marginal cost to $(1-\beta)^2$ to simplify the algebra. This implies that all machine prices in the U.S. will be $\chi^U = (1-\beta)$.

LDC technology firms can copy U.S. machines at some small cost ξ, and sell them to firms in their own country (see Section 5.3 for a model of technology adoption by LDCs). The enforcement of intellectual property rights will determine how much of the revenues generated by the sale of machines in the LDCs will accrue to monopolists in the U.S. I assume that U.S. R&D monopolists receive a fraction μ of the revenue, so μ is an index of the extent of intellectual property rights enforcement.[11]

Will LDC firms use domestic technologies or U.S. technologies? As long as $\theta^j q_s^U(i) > q_s^j(i)$ for $s = l, h$ and all j and i, it is more productive for LDC firms to use U.S. technologies. In fact, I assume that at time $t = 0$ the somewhat stronger condition $(1-\beta)\theta^j q_s^U(i) > q_s^j(i)$ is satisfied for $s = l, h$ and all j and i. This condition ensures that even when U.S. technologies sell at the monopoly price, $(1-\beta)$, and domestic technologies sell at marginal cost, $(1-\beta)^2$, LDC producers prefer to use U.S. technologies. It therefore guarantees that LDC technology monopolists will always adopt U.S. technologies and set the monopoly price, *i.e.* $\chi = (1-\beta)$

10. This might imply that the x's here may better correspond to intermediate goods rather than machines. This is without any substantive implications. Moreover, it is straightforward to introduce slow depreciation of machines, which complicates the expressions, but does not affect any of the results.

11. Throughout LDC firms are not allowed to re-export to the U.S. market, so μ does not affect domestic revenues for U.S. R&D firms.

for all machines,[12] and $\tilde{q}_s^j(i) = \theta^j q_s^U(i)$. Moreover, the fact that LDC firms prefer U.S. technologies implies that there will be no research in LDCs, so in all future dates, we will also have $(1-\beta)\theta^j q_s^U(i) > q_s^j(i)$ and $\tilde{q}_s^j(i) = \theta^j q_s^U(i)$.

Now substituting the monopoly machine price $\chi^j = (1-\beta)$ into the demand functions given by (15), we obtain the quantity of machines used in production as $x_l^j(\tilde{q}_l^j(i)) = (p_l^j)^{1/\beta}\tilde{q}_l^j(i)L^j$ and $x_h^j(\tilde{q}_h^j(i)) = (p_h^j)^{1/\beta}\tilde{q}_h^j(i)H^j$ in country j. Combining these expressions with (14), outputs of the two goods in country j are

$$Y_l^j = (p_l^j)^{(1-\beta)/\beta}\tilde{Q}_l^j L^j \quad \text{and} \quad Y_h^j = (p_h^j)^{(1-\beta)/\beta}\tilde{Q}_h^j H^j, \tag{16}$$

where $\tilde{Q}_s^j \equiv \int_0^1 \tilde{q}_s^j(i)di$, for $s = l, h$, is a measure of the aggregate (average) productivity of machines used in sector s in country j. I will sometimes refer to $\tilde{Q}_l^j$ as labour-complementary technology and to $\tilde{Q}_h^j$ as skill-complementary technology, since they correspond to the average productivity of machines used with the two types of labour. Equation (16) shows that the term $(p_s^j)^{(1-\beta)/\beta}\tilde{Q}_s^j$ corresponds to A_s^j in terms of the previous section (see equation (4)). It highlights that there are two forces affecting the productivity of labour. The first is the state of technology (or the technology frontier as given by $\tilde{Q}_s^j$), while the second is product prices. The latter force implies that two countries facing the same technology frontier may use different "techniques". In particular, as shown by equation (15), the capital–labour (machine–labour) ratios will depend on product prices, so these countries will generally have different factor productivities because of the different choices of techniques (see Acemoglu and Zilibotti, 2001, for the implications of this for cross-country productivity differences).

The wage, the marginal product of labour, is therefore $w_s^j = \beta(p_s^j)^{1/\beta}\tilde{Q}_s^j$. Since $\tilde{q}_s^j(i) = \theta^j q_s^U(i)$, we also have that $\tilde{Q}_s^j = \theta^j Q_s^U$, so $\tilde{Q}_h^j/\tilde{Q}_l^j = Q_h^U/Q_l^U$. Hence, denoting $Q_s^U = Q_s$ for $s = l, h$ to simplify the notation, the skill premium in country j is

$$\omega^j \equiv \frac{w_h^j}{w_l^j} = (p^j)^{1/\beta}\frac{Q_h}{Q_l}. \tag{17}$$

Skill premia therefore depend on technology and product prices. In two countries with the same technology and with the same product prices, the relative wage should be the same. In this section, skill premia differ between the U.S. and the LDCs because, in the absence of international trade, their product prices differ. Simple algebra using (3), (14) and (16) gives the relative price p^j as a function of H^j/L^j:

$$p^j = \left[\left(\frac{1-\gamma}{\gamma}\right)^{-\varepsilon}\frac{Q_h}{Q_l}\frac{H^j}{L^j}\right]^{-\frac{\beta}{1+\beta(\varepsilon-1)}}. \tag{18}$$

An increase in H^j/L^j therefore increases the relative supply of skill-intensive goods and depresses p^j. Now, combining this with (17), we obtain

$$\omega^j = \left[\left(\frac{1-\gamma}{\gamma}\right)^{-\varepsilon}\frac{H^j}{L^j}\right]^{-\frac{1}{1+\beta(\varepsilon-1)}}\left(\frac{Q_h}{Q_l}\right)^{\frac{\beta(\varepsilon-1)}{1+\beta(\varepsilon-1)}}. \tag{19}$$

This equation implies that for a given state of technology (skill bias) as captured by Q_h/Q_l, the skill premium ω^j is decreasing in the supply of skills. This implies that across countries sharing the same technology, there will be a decreasing relationship between the relative supply of skills

12. Because of the copying cost, ξ, only one firm will copy each U.S. technology. If more than one firm did so, they would compete *à la* Bertrand, and would make negative profits. If $\xi = 0$, then there would be zero profits from machine sales in the LDCs, and the results would be identical to the case with $\mu = 0$ here.

and the skill premium, as shown by the constant-technology demand curve CT in Figure 2 (though notice that the term $1 + \beta(\varepsilon - 1)$ has now replaced ε in (7) as the elasticity of the relative demand for skills).

3.2. *Equilibrium technical change*

I now analyse the forces that determine the equilibrium skill bias of technologies. Recall that new technologies are developed only in the U.S. because all LDC firms prefer to use U.S. technologies. The value of owning the leading vintage of machine $q_s(i)$ in sector s is given by a standard Bellman equation:

$$rV_s(q_s(i)) = \bar{\pi}_s(q_s(i)) - z_s(q_s(i))\phi(z_s(q_s(i)))V_s(q_s(i)) + \dot{V}_s(q_s(i)), \tag{20}$$

where $z_s(q_s(i))\phi(z_s(q_s(i)))$ is the flow rate of a new invention, capturing the flow rate at which the existing monopolist is being replaced, and $\bar{\pi}_s(q_s(i))$ is the total flow profit from selling a machine of vintage $q_s(i)$, given by

$$\bar{\pi}_s(q_s(i)) = \pi_s^U(q_s(i)) + \mu \sum_{j=1}^{J} \pi_s^j(q_s(i)),$$

where $\mu \leq 1$ is the fraction of monopoly revenue from LDCs received by U.S. R&D monopolists, and $\pi_s^j(q_s(i))$ is the flow profit from selling a machine of vintage $q_s(i)$ in country j. Equation (15) and the fact that marginal cost of machine production is $(1-\beta)^2$ and the price is $\chi_s^j = 1 - \beta$ for all s and j imply that flow profits are $\pi_s^j(q_s(i)) = \beta(1-\beta)x_s^j(q_s(i))$.

Free entry into R&D activities implies that an additional dollar spent for research must yield a return equal to cost:[13]

$$\phi(z_s(q_s(i)))V_s(\lambda q_s(i)) = \beta(1-\beta)\lambda q_s(i), \tag{21}$$

where notice that the argument of the value function is $\lambda q_s(i)$ since R&D on a machine of quality $q_s(i)$ leads to the discovery of a machine of quality $\lambda q_s(i)$ and I have used the normalization $B \equiv \beta(1-\beta)\lambda$.

An equilibrium requires that firms choose the profit-maximizing technology and rent the profit-maximizing amounts of all inputs; innovators follow the profit-maximizing pricing policy; product, intermediate good and labour markets clear; and there is no opportunity for any research firm to enter (or exit) and increase its profits. Equations (15), (18)–(21) ensure these conditions.

To highlight the forces that shape the skill bias of technology most clearly, I start with the case in which $\mu = 0$, so there is no intellectual property rights enforcement in the LDCs. Although LDC technology monopolists copy and sell U.S. technologies, they do not pay patent fees or royalties to U.S. firms.

I start with the balanced growth path (BGP) along which $\dot{V} = 0$. Imposing this condition, equations (20) and (21) imply that in BGP

$$\bar{\pi}_s(\lambda q_s(i)) = \beta(1-\beta)\lambda \frac{r + z_s(q_s(i))\phi(z_s(q_s(i)))}{\phi(z_s(q_s(i)))} q_s(i) \tag{22}$$

for any machine i and $s = l$ or h. This equation relates BGP research effort to the profitability of innovation in that sector. The fact that $\phi(z)$ is decreasing and $z\phi(z)$ is increasing in z ensures that the R.H.S. of (22) is increasing in $z_s(q_s(i))$, so a greater profitability translates into greater research effort.

13. This expression assumes that R&D firms are small and do not take into account their impact on the aggregate innovation probability which is the natural assumption in this context. If alternatively we assume that there is a R&D consortium, the free entry condition would become $[\phi(z_s(q_s(i))) + z_s(q_s(i))\phi'(z_s(q_s(i)))]V_s(\lambda q_s(i)) = \beta(1-\beta)\lambda q_s(i)$. This does not affect any of the results of the analysis.

Since $\mu = 0$, *i.e.* since there are no intellectual property rights in the LDCs, we have $\bar{\pi}_l(\lambda q_l(i)) = \beta(1-\beta)\lambda(p_l^U)^{1/\beta}L^U q_l(i)$ and $\bar{\pi}_h(\lambda q_h(i)) = \beta(1-\beta)\lambda(p_h^U)^{1/\beta}H^U q_h(i)$. First, note that these profits are linear in $q_s(i)$, so the BGP condition (22) implies that research effort devoted to a machine is independent of its quality, $q_s(i)$. So the same research effort, say z_h, will be devoted to the discovery of all skill-complementary technologies, and the same research effort, z_l, will be devoted to the discovery of all labour-complementary technologies. We therefore only have to determine two variables, z_l and z_h. Moreover, because of the absence of international intellectual property rights, the profitabilities of new innovations, and therefore of research effort, depend only U.S. supplies and prices.

Using the free-entry and BGP equilibrium conditions, (21) and (22), for $s = l$ and h, we obtain

$$(p^U)^{1/\beta}\frac{H^U}{L^U} = \frac{r + z_h\phi(z_h)}{\phi(z_h)} \cdot \frac{\phi(z_l)}{r + z_l\phi(z_l)}.$$

This equation implies that z_h/z_l, relative research effort directed at skill-complementary technologies, is increasing in the relative profitability of developing skill-complementary machines, and therefore in $(p^U)^{1/\beta}H^U/L^U$.

As a result, the direction of technical change is determined by two factors: (1) *The price effect:* technologies producing more expensive goods will be upgraded faster. Because goods using the scarce factor will command a higher price (see (18) above), this effect implies that there will be more innovation directed at the scarce factor. (2) *The market size effect:* a larger clientele for the technology leads to more innovation. Since the clientele for a technology is effectively the workers who use it, the market size effect encourages innovation for the more abundant factor. Equilibrium bias in technical change is determined by these two opposing forces. A greater supply of skilled workers, via the price effect, induces the development of more labour-complementary technologies. When there are more skilled workers, the size of the market for skill-complementary technologies is also larger, and this encourages further skill-biased technical change.

More formally, for BGP, we need $\dot{V}_s = 0$, which implies that Q_h/Q_l has to remain constant, so $z_l = z_h$. Equation (22) then implies that along the BGP there is a technology equilibrium condition given by

$$p^U = \left(\frac{H^U}{L^U}\right)^{-\beta}. \tag{23}$$

Intuitively, BGP requires both sectors to grow at the same rate, hence $z_l = z_h$. So the demand for skill-complementary technologies relative to labour-complementary machines should be independent of H^U/L^U, and the price and market size effects should exactly balance out, which is ensured by the technology equilibrium equation (23).

Equations (18) and (23) imply that the BGP relative productivity of skilled workers satisfies

$$\frac{Q_h}{Q_l} = \left(\frac{1-\gamma}{\gamma}\right)^{\varepsilon}\left(\frac{H^U}{L^U}\right)^{\beta(\varepsilon-1)}. \tag{24}$$

Q_h/Q_l, the average quality of skill-complementary machines relative to labour-complementary machines, is the measure of equilibrium skill bias. Equation (24) implies that equilibrium skill bias is determined by the relative supply of skills in the U.S., and the parameter $\beta(\varepsilon - 1)$ captures the strength, and the sign, of this directed technology effect.[14]

14. Q_h/Q_l is a measure of skill-complementary technologies relative to labour-complementary technologies. The fact that Q_h/Q_l also corresponds to the "skill bias" of technology is a consequence of the elasticity of substitution, ε, being greater than 1. See Acemoglu (2002).

Because $\varepsilon > 1$, *i.e.* because skill- and labour-intensive goods are relatively close substitutes, of the two influences on the direction of technical change, the market size effect is more powerful.[15] Since profits to innovation are proportional to market size, they are proportional to the number of workers using the technology. Therefore, when H^U/L^U increases, innovation and R&D in the skill-intensive sector become more profitable, inducing Q_h/Q_l to increase. This provides an attractive explanation for the patterns shown in Figure 1, whereby the steady increase in the relative supply of skilled workers in the U.S. over the post-war period is the underlying cause of the secular increase in the demand for skilled workers (this increase itself can be a response to the rise in the skill premium, see Appendix C).

Finally, the BGP research effort level can now be determined from (22), (23) and (24) by imposing $z_l = z_h = z$.

$$\frac{r + z\phi(z)}{\phi(z)} = \left[(1-\gamma)(H^U)^{1+\eta} + \gamma(L^U)^{1+\eta}\right]^{\frac{1}{1+\eta}}, \tag{25}$$

where I define $\eta \equiv \beta(\varepsilon - 1) - 1$. Finally, using the analysis so far and the skill premium equation (19), we have (proof in the text):

Proposition 1. *Suppose there is no international trade and no enforcement of intellectual property rights in the LDCs* (i.e. $\mu = 0$). *Then, there is a unique BGP where in all countries, both sectors and total output grow at the rate* $(\lambda - 1)z\phi(z)$ *with* z *given by* (25). *Along the BGP,* Q_h/Q_l *is given by* (24), *so a greater relative supply of skills in the U.S.,* H^U/L^U, *causes skill-biased technical change* (*increases* Q_h/Q_l). *The BGP skill premium in the U.S. is*

$$\omega^U = \left(\frac{1-\gamma}{\gamma}\right)^{\varepsilon}\left(\frac{H^U}{L^U}\right)^{\eta}. \tag{26}$$

The skill premium in country j *is*

$$\omega^j = \left(\frac{1-\gamma}{\gamma}\right)^{\varepsilon}\left(\frac{H^U}{L^U}\right)^{\frac{(1+\eta)^2}{2+\eta}}\left(\frac{H^j}{L^j}\right)^{-\frac{1}{2+\eta}}, \tag{27}$$

where recall that $\eta \equiv \beta(\varepsilon - 1) - 1$.

The first important result is that the degree of skill bias, Q_h/Q_l, is endogenous and depends on the U.S. relative supply of skills. A larger relative supply translates into a greater skill bias of technology. Moreover, in the unique BGP there is a monotonic relationship between the relative supply of skilled workers in the U.S. and their relative wage. However, because of the endogeneity of skill bias, this relationship can be either increasing or decreasing. If technology were exogenous in this economy in the sense that Q_h/Q_l were constant or changing exogenously, the skill premium would be a decreasing function of H^U/L^U as in Section 2. Instead, when technology is endogenous, a greater H^U/L^U encourages more R&D activity towards the skill-complementary technologies. As a result, the long-run relative demand curve for skills will be flatter than the constant-technology demand curve, CT, for example like ET_1 in Figure 2. Furthermore, if the directed technology effect, $\beta(\varepsilon - 1)$ from (24), is large enough, η will be positive, and the long-run relative demand curve for skills will be *upward sloping* as ET_2 in Figure 2. In this case, the higher supply of skilled workers in the U.S. may lead to higher returns to skills, in line with the recent developments in the U.S. labour market.[16]

15. See Acemoglu (2002) for the analysis of the case in which $\varepsilon < 1$. Even in this case, a greater relative supply of skills causes skill-biased technical change.

16. Notice that to ensure a positive skill premium in equations (26) and (27), we need $((1-\gamma)/\gamma)^{-\varepsilon} > (H^U/L^U)^{\eta}$.

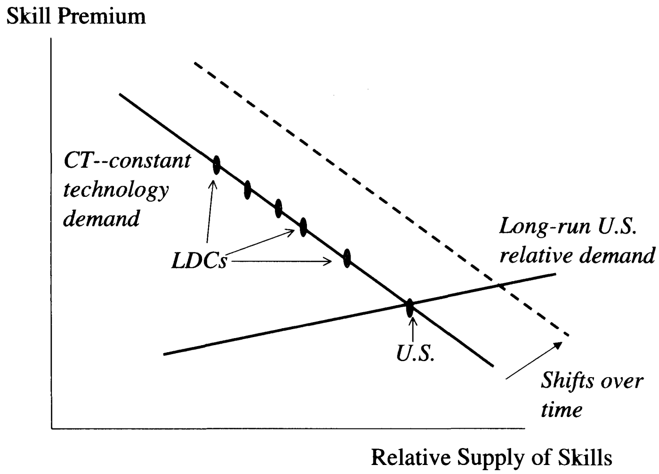

FIGURE 3

Cross-country and time-series variation in skill premia when $\eta > 0$

Equation (27), on the other hand, shows that the cross-country relationship between the supply of skills and skill premia will be decreasing. In particular, a higher H^j/L^j leads to a lower skill premium, because among the LDCs, changes in the supply of skills move a country along the constant technology demand curve for skills, CT, in Figure 2.

It is also noteworthy that an increase in the U.S. supply of skills, H^U/L^U, leads to an increase in the skill premium in the LDCs. Therefore, both the time-series and the cross-country patterns implied by this model can be summarized in Figure 3.[17] All countries are along a downward sloping relative demand curve, but this relative demand curve shifts out over time in response to changes in the supply of skilled workers in the U.S. In particular, when $\eta > 0$, these shifts trace out an upward sloping long-run U.S. relative demand curve for skills.

Finally, it is useful to observe that with η positive, a possible explanation for the large increase in the demand for skills during the 1980's is the substantial increase in the supply of skilled workers in the U.S. during the 1960's and 1970's. As argued in Acemoglu (1998), this increase in the supply of skills could have caused rapid skill-biased technical change, raising wage inequality in the U.S. and in countries using U.S. technology. In the next section, I propose a complementary mechanism for the increase in wage inequality in both the U.S. and the LDCs: increased international trade between these countries.

The next proposition summarizes the transitional dynamics and is proved in Appendix B.

Proposition 2. *If $\phi'(\cdot) < 0$, then the system is locally saddlepath stable. In particular, if $Q_h/Q_l < ((1-\gamma)/\gamma)^\varepsilon (H^U/L^U)^{1+\eta}$, then $z_h > z_l$, and if $Q_h/Q_l > ((1-\gamma)/\gamma)^\varepsilon (H^U/L^U)^{1+\eta}$, then $z_h < z_l$.*

If $\phi'(\cdot) = 0$, then the economy immediately jumps to the BGP.

An implication of this proposition is that, as long as $\phi'(\cdot) < 0$, Q_h/Q_l does not immediately react to an imperfectly anticipated increase in H^U/L^U: the economy first moves along a downward sloping relative demand for skills as CT in Figure 2. This will be followed by a period

17. The working paper version, Acemoglu (1999*b*), presented evidence consistent with a negative relationship between skill premia and the supply of skills across a set of countries using data from Barro and Lee (1993) and Psacharopoulos (1994).

of rapid skill-biased technical change with $z_h > z_l$. This is interesting in part because this pattern might provide an explanation for why the U.S. skill premium fell during the 1970's in the face of the rapid increase in the supply of skilled workers, and then increased sharply during the 1980's.

The above discussion has provided an explanation for the cross-country and time-series patterns of skill premia over the past 60 years, relying on the notion that $\eta > 0$. Is $\eta > 0$ empirically plausible? There are two ways to tackle this question. First, in this simple set-up, $\eta \equiv \beta(\varepsilon - 1) - 1$, so one can investigate whether for plausible values of β and ε, η can be positive. The elasticity of substitution between skilled and unskilled workers is now $\sigma = 1 + \beta(\varepsilon - 1) = 2 + \eta$ (from equation (19), $\partial\omega^j/\partial(H^j/L^j)\,|_{Q_h/Q_l} = -1/(1 + \beta(\varepsilon - 1))$). Taking the value of 1·4 for this elasticity implies that $\eta = -0{\cdot}6$, while a value for the elasticity greater than 2 implies that $\eta > 0$. So for η to be positive, we need an elasticity of substitution greater than 2, which is on the higher side of the estimates, but still plausible, and consistent with a number of studies (*e.g.* Angrist (1995), Card and Lemieux (2001)). Moreover, the model here does not feature any state-dependence in the R&D process—that is, greater Q_h does not make future skill-complementary innovations easier relative to labour-complementary innovations. Acemoglu (2002) shows that when there is such state-dependence, an upward-sloping relative demand curve requires an elasticity of substitution less than 2.[18]

Second, equation (26) gives the long-run relationship between skill premia and the relative supply of skills as $\ln \omega^U = \eta \ln(H^U/L^U)$. The data shown in Figure 1 can be used to run a regression of this form. This regression leads to an estimate of η equal to 0·13 with standard error 0·02, which is consistent with a positive value for η, though of course the skill premium and the relative supply of skills might have increased simultaneously, for different reasons over this time period.

3.3. *Intellectual property rights in the LDCs*

The analysis so far assumed no enforcement of intellectual property rights in the LDCs. In practice U.S. firms do receive some royalties and patent fees from companies in the LDCs. I now show that the qualitative results highlighted above are not affected in this case. To do this suppose that $\mu > 0$, that is, R&D firms in the U.S. capture some of the revenues generated by machine sales in the LDCs. Equation (20) still determines the value of innovation, and equation (21) is the free-entry condition. The only difference is that total profits now include profits from machine sales in the LDCs. Balanced growth again requires the same research effort, z, to be allocated to all types of machines. In particular, in BGP we need

$$\bar{\pi}_l(\lambda q_l(i)) = \beta(1-\beta)\lambda\Big[(p_l^U)^{1/\beta}L^U + \mu\sum\nolimits_{j=1}^{J}\theta^j(p_l^j)^{1/\beta}L^j\Big]q_l(i) = \beta(1-\beta)\lambda\frac{r + z\phi(z)}{\phi(z)}q_l(i) \tag{28}$$

and

$$\bar{\pi}_h(\lambda q_h(i)) = \beta(1-\beta)\lambda\Big[(p_h^U)^{1/\beta}H^U + \mu\sum\nolimits_{j=1}^{J}\theta^j(p_h^j)^{1/\beta}H^j\Big]q_h(i) = \beta(1-\beta)\lambda\frac{r + z\phi(z)}{\phi(z)}q_h(i), \tag{29}$$

18. For example, we can have the relative cost of skill-complementary R&D decline proportionally with $(Q_h/Q_l)^{\zeta}$ for some $\zeta < 1$ (the modelling is parallel to that in Section 5.3). In this case, it is straightforward to show that the skill premium in the U.S., ω^U, is proportional to $(H^U/L^U)^{(\beta(\varepsilon-1)-\zeta)/(1+\zeta\beta(\varepsilon-1))}$. For example, if $\zeta > 0{\cdot}6$, then the long-run relative demand for skills will be upward sloping for an elasticity of substitution between skilled and unskilled workers greater than or equal to 1·4.

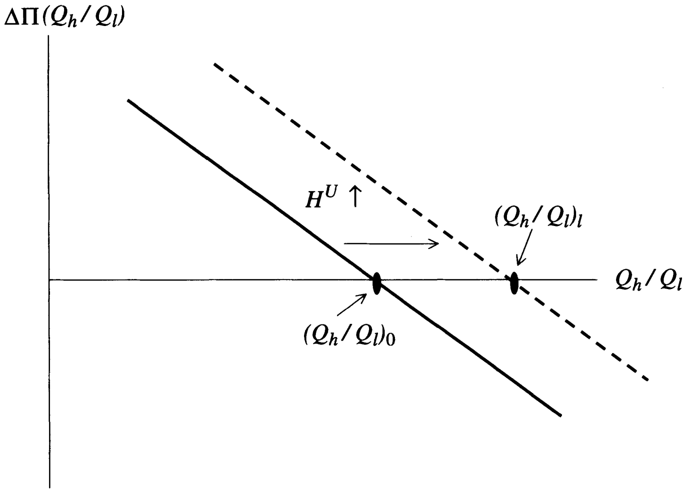

FIGURE 4

The determination of the skill bias of technology with intellectual property rights enforcement in the LDCs

where, as before, the quality levels of individual machines, $q_l(i)$ or $q_h(i)$, cancel out from both sides. Then, we can see that the BGP requires

$$\Delta\Pi(Q_h/Q_l) \equiv \frac{\bar{\pi}_h(\lambda q_h(i))}{\lambda q_h(i)} - \frac{\bar{\pi}_l(\lambda q_l(i))}{\lambda q_l(i)}, \tag{30}$$

with $\bar{\pi}_h$ and $\bar{\pi}_l$ given by (28) and (29). Here $\Delta\Pi(Q_h/Q_l)$ is a function of the skill bias of technology, Q_h/Q_l, because prices in these equations are functions of Q_h/Q_l. In particular, from equations (6) and (18), it is straightforward to verify that p_l^j is increasing in Q_h/Q_l, while p_h^j is decreasing in Q_h/Q_l for all $j = U, 1, 2 \dots J$ (see Appendix B). So the BGP condition $\Delta\Pi(Q_h/Q_l) = 0$ defines a downward-sloping curve when plotted against Q_h/Q_l as in Figure 4, and has a unique intersection with the horizontal axis, corresponding to a unique BGP level of skill bias of technology, $(Q_h/Q_l)_0$ in the figure.

Comparative statics follow immediately from this figure. As long as $\varepsilon > 1$, an increase in H^U (or a reduction in L^U) shifts out of this curve, increases Q_h/Q_l, and causes skill-biased technical change, exactly as in the case without property rights. An increase in the degree of intellectual property rights enforcement, μ, shifts the curve to the left, and reduces Q_h/Q_l. The reason for this is clear: the LDCs are more skill-scarce than the U.S., and a greater enforcement of intellectual property rights creates a market size effect favouring unskilled workers. The following proposition, proved in Appendix B, states these results:

Proposition 3. *Consider the case in which there is some degree of intellectual property rights enforcement in the LDCs, i.e. $\mu > 0$. Then, there exists a unique BGP skill bias Q_h/Q_l such that $\Delta\Pi(Q_h/Q_l) = 0$. An increase in the relative supply of skills in the U.S., H^U/L^U, increases Q_h/Q_l and an increase in μ reduces Q_h/Q_l.*

Therefore, as in the case without property rights in the LDCs, the skill bias of technology responds to the market size effect. In particular, an increase in the number of skilled workers in the U.S. causes skill-biased technical change. In addition, now an increase in the number of skilled workers in the LDCs, H^j, also causes skill-biased technical change. The important implication is that irrespective of the degree of intellectual property rights enforcement in the LDCs, the framework here predicts that technology should have become more skill biased over the past 60 years because the relative supply of skilled workers has increased substantially both in the U.S. and in the rest of the world.

The analysis so far has treated the supply of skills as exogenous. The skill premium in a country is likely to affect the willingness of individuals to undertake investments in human capital, and this will have a number of implications for the interpretation of cross-country and time-series patterns of the post-war period. Appendix C generalizes this set-up to endogenize the supply of skills. There are three main implications from this extension. First, with the supply of skills endogenized, there can be multiple equilibria. Second, the framework now offers an explanation for the joint behaviour of the supply of skills and technology for the post-war period: it suggests that along the transition path, we can have both the supply of skills increasing and technology becoming more skill biased. Third, the framework suggests that greater supply of skills in the U.S., through its effect on technology and skill premia, encourages further investment in skills in the LDCs.

4. TRADE OPENING AND CHANGES IN SKILL PREMIA

I now consider the impact of an increase in the volume of trade on patterns of skill premia. To simplify the discussion, I compare the two extreme cases of no international trade and free international trade. I also assume that there is no change in the enforcement of intellectual property rights in the LDCs as a result of trade opening, so I focus on the case where only international trade patterns change. From the results reported above, the implications of a greater degree of intellectual property rights enforcement follow readily. Finally, it is useful to observe at this point that despite the emphasis on the case with $\eta > 0$ in the previous section, the results in this section do not depend on the sign of η.

4.1. *Trade and skill-biased technical change*

Suppose that there is free trade in Y_h and Y_l. This will affect innovation incentives through its effect on product prices. In particular, in the presence of free trade, all product prices will be equalized across countries, rather than being determined by domestic supplies as in equation (5). The world relative price of skill-intensive goods will be given by the world relative supply through an equation similar to (8). More specifically, similar arguments to before imply that

$$Y_l^j = (\hat{p}_l)^{(1-\beta)/\beta}\tilde{Q}_l^j L^j \qquad \text{and} \qquad Y_h^j = (\hat{p}_h)^{(1-\beta)/\beta}\tilde{Q}_h^j H^j,$$

which differ from (16) because the world prices of the two goods, rather than country-specific prices, feature in output. Using the fact all consumers in the world face the same relative price and will have the same relative consumption of skill-intensive and labour-intensive goods, and exploiting $\tilde{Q}_s^j = \theta^j Q_s^j$ for $j = 1, 2, \dots, J$, we have the world relative price of skill-intensive goods as

$$\hat{p} = \left[\left(\frac{1-\gamma}{\gamma}\right)^{-\varepsilon}\left(\frac{Q_h}{Q_l}\right)\left(\frac{H^W}{L^W}\right)\right]^{-\frac{\beta}{1+\beta(\varepsilon-1)}}, \tag{31}$$

where recall that $H^W \equiv H^U + \sum_{j=1}^J \theta^j H^j$ and $L^W \equiv L^U + \sum_{j=1}^J \theta^j L^j$.

Equation (20) still determines the value of innovation, and equation (21) is the free-entry condition, but total profits are now given by

$$\bar{\pi}_l(\lambda q_l(i)) = \beta(1-\beta)\lambda\hat{p}_l^{1/\beta}\Big[L^U + \mu\sum\nolimits_{j=1}^J \theta^j L^j\Big]q_l(i),$$

and

$$\bar{\pi}_h(\lambda q_h(i)) = \beta(1-\beta)\lambda \hat{p}_h^{1/\beta}\Big[H^U + \mu \sum\nolimits_{j=1}^{J} \theta^j H^j\Big] q_h(i),$$

which differ from previous expressions because, instead of country-specific good prices, they feature the world prices of labour- and skill-intensive goods, $\hat{p}_l$ and $\hat{p}_h$.

Let me once again start with the case in which there are no intellectual property rights in the LDCs, *i.e.* $\mu = 0$, and first discuss the BGP. With $\mu = 0$, the BGP condition is $\bar{\pi}_l(\lambda q_l(i))/\lambda q_l(i) = \bar{\pi}_h(q_h(i))/\lambda q_h(i)$, which implies $\hat{p}_l^{1/\beta} L^U = \hat{p}_h^{1/\beta} H^U$, or

$$\hat{p} = \left(\frac{H^U}{L^U}\right)^{-\beta}. \tag{32}$$

This is similar to (23), except that on the left-hand side we have the world relative price of skill-intensive goods rather than the U.S. price. Combining this equation with the world relative price, (31), we can solve for the BGP skill bias of technology in the presence of free trade as

$$\frac{\hat{Q}_h}{\hat{Q}_l} = \left(\frac{1-\gamma}{\gamma}\right)^{\varepsilon} \left(\frac{H^W}{L^W}\right)^{-1} \left(\frac{H^U}{L^U}\right)^{1+\beta(\varepsilon-1)}. \tag{33}$$

I have written the technology terms as $\hat{Q}_h$ and $\hat{Q}_l$ to emphasize that these terms will be different from those that prevailed in the last section without international trade. Comparing (33) to (24) and using the fact that $H^W/L^W < H^U/L^U$, we obtain

$$\frac{\hat{Q}_h}{\hat{Q}_l} > \frac{Q_h}{Q_l}. \tag{34}$$

Therefore, trade increases the skill bias of technology from Q_h/Q_l to $\hat{Q}_h/\hat{Q}_l$, that is, trade *induces skill-biased technical change*. This result follows from the price effect on the direction of technical change emphasized above: international trade increases the relative price of skill-intensive goods, and the higher relative price of skill-intensive goods encourages further skill-biased technical change.[19]

There is an additional and striking implication: trade does not affect the long-run relative prices of skill-intensive goods in the U.S. Before trade this relative price was given by $p^U = (H^U/L^U)^{-\beta}$ (from equation (23) above), and now the world relative price is $\hat{p} = (H^U/L^U)^{-\beta}$ (from equation (32)). Therefore, because of trade's effect on technical change, the BGP relative price of skill-intensive goods faced by U.S. consumers remains unchanged: the induced skill-biased technical change ensures that the world relative supply of skill-intensive goods increases sufficiently to reduce the world relative price to the pre-trade U.S. level.

This result may, at first, appear somewhat paradoxical, since the reason why technical change becomes more skill-biased is the price effect—*i.e.* the fact that trade increases the relative price of skill-intensive goods in the U.S. But it is quite intuitive, and simply reflects the strength of the directed technology effect. To see the intuition, note that the relative price of skill-intensive goods plays two roles in this model. The first is to clear the market for goods (*i.e.* equation (11)), and the second is to ensure equilibrium in the technology market (*i.e.* equation (23)). Since the technology equilibrium condition relates the relative price of skill-intensive goods to the relative supplies in the U.S. market, which do not change, the long-run equilibrium price of skill-intensive goods cannot change either. So there has to be a sufficient amount of skill-biased technical change to increase the supply of skill-intensive goods to achieve the same relative price

19. Because the degree of enforcement of property rights has not changed, the market sizes for different types of technologies remain the same as before trade.

after trade opening. We will see below that with transitional dynamics, the relative price of skill-intensive goods in the U.S. first increases and then returns to its pre-trade level.

Next, recall that the skill premium is still given by equation (17), and $\tilde{Q}_h^j/\tilde{Q}_l^j$ is the same in all countries. Also, international trade implies that the relative price of skill-intensive goods is the same in all countries. Therefore, skill premia in all countries are now equalized. Notice, however, that this observation does not guarantee factor price equalization, since U.S. technologies are typically less productive when used in the LDCs (*i.e.* $\theta^j \leq 1$), making U.S. workers earn higher wages than LDC workers. To calculate the post-trade world skill premium, $\hat{\omega}$, I use equation (17) together with (31) and (33)

$$\hat{\omega} = \left(\frac{1-\gamma}{\gamma}\right)^{\varepsilon} \left(\frac{H^U}{L^U}\right)^{2+\eta} \left(\frac{H^W}{L^W}\right)^{-1}, \tag{35}$$

where recall that $\eta \equiv \beta(\varepsilon-1)-1$. That $\hat{\omega} > \omega^U$ immediately follows from $H^W/L^W < H^U/L^U$. For comparison, also note that if the skill bias of technology remained at its U.S. pre-trade level given by (24), the world (and U.S.) skill premium would have been

$$\bar{\omega} = \left(\frac{1-\gamma}{\gamma}\right)^{\varepsilon} \left(\frac{H^U}{L^U}\right)^{\frac{(1+\eta)^2}{2+\eta}} \left(\frac{H^W}{L^W}\right)^{-\frac{1}{2+\eta}} < \hat{\omega}. \tag{36}$$

The fact that $\hat{\omega} > \bar{\omega}$, *i.e.* that induced technical change contributes to the increase in wage inequality, again follows from $H^W/L^W < H^U/L^U$.

Equations (34)–(36) give the major result of this paper. They imply that trade opening induces skill-biased technical change in the U.S., and increases the skill premium more than would have been the case with constant technology.

What happens to skill premia in the LDCs? Using equations (27) and (35), we obtain that the skill premium in country j will increase, *i.e.* $\hat{\omega} > \omega^j$, if and only if

$$\frac{H^j}{L^j} > \left(\frac{H^W}{L^W}\right)^{2+\eta} \left(\frac{H^U}{L^U}\right)^{-(1+\eta)}. \tag{37}$$

Clearly this is satisfied for $j = U$, since $H^W/L^W < H^U/L^U$, reiterating that $\hat{\omega} > \omega^U$. More importantly, LDCs for which condition (37) holds will experience an increase in inequality, while the rest will experience a decline. Condition (37) is more likely to be satisfied for LDCs that are relatively skill-abundant, while LDCs that are most skill-scarce should experience a decline in inequality as in the standard trade models. This implication is consistent with the evidence discussed in footnote 6 that, over the 1980's, wage inequality increased in a number of LDCs, while declining in others. It can also be empirically investigated in more detail using microdata from LDCs, and relating wage inequality changes to trade opening and relative supply of skills.

It is also straightforward to characterize the transitional dynamics of the world economy. Suppose the opening to trade is unanticipated. Then immediately after trade opening, Q_h/Q_l is less than its BGP level, so we will have $z_h > z_l$, and the skill bias of technology will gradually increase. Over this process, as shown in Figure 5, the world skill premium, $\hat{\omega}$, increases and the world relative price of skill-intensive goods, $\hat{p}$, falls. We thus have (the proof is in the Appendix):

Proposition 4. *Assume that $\mu = 0$ and $\phi'(\cdot) < 0$. Suppose that the world economy opens to international trade, and this change is unanticipated. After trade opening we have $z_h > z_l$. The BGP value of $z_h = z_l = z$ is given by (25), and hence the growth rate of the world economy is unchanged, $(\lambda - 1)z\phi(z)$ with z given by (25). The skill bias of technology increases from Q_h/Q_l given by (24) to $\hat{Q}_h/\hat{Q}_l$ given by (33). The skill premium in the U.S. immediately increases from ω^U as given by (26) to $\bar{\omega}$ as given by (36), and then gradually rises to $\hat{\omega} > \omega^U$ as given by (35).*

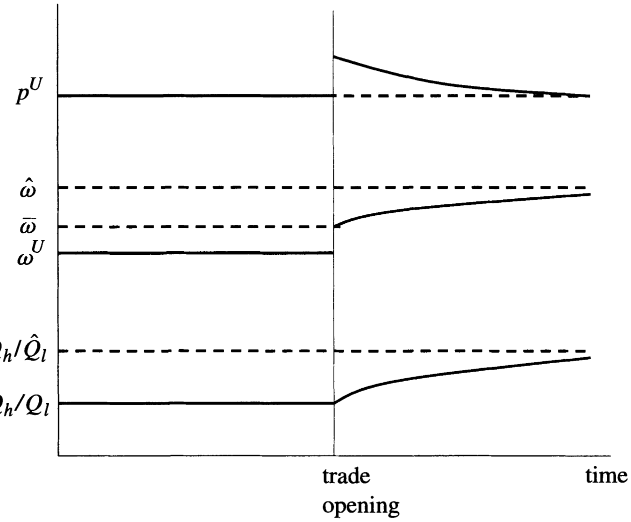

FIGURE 5

Dynamics of the U.S. relative price of skill-intensive goods, U.S. skill premium and equilibrium skill bias after trade opening

The skill premium in country $j > 0$ is higher in BGP if (37) *is satisfied, and lower otherwise. The relative price of skill-intensive goods in the U.S. immediately increases from $p^U = (H^U/L^U)^{-\beta}$ to $\hat{p}$ as given by* (31) *evaluated with Q_h/Q_l given by* (24). *This world relative price of skill-intensive goods then declines asymptotically to its BGP value $\hat{p} = p^U = (H^U/L^U)^{-\beta}$.*

If instead $\phi'(\cdot) = 0$, then the economy immediately jumps to the new BGP after trade opening, and there is no change in the relative price of skill-intensive goods in the U.S.

Overall, there are a number of conclusions significantly different from the standard trade models. First, endogenous (directed) technical change implies that trade with the LDCs induces skill-biased technical change. The impact of trade on the U.S. labour market may therefore be much larger than predicted by standard trade models. Second, because trade induces skill-biased technical change, the productivity of skilled workers increases. Third, there is a force counteracting the decline in inequality in the LDCs implied by trade: these economies use U.S. technologies, which are becoming more skill-biased.

Finally, trade first increases the relative price of skill-intensive goods in the U.S., but then eventually this relative price returns to its pre-trade U.S. level. This result is important because changes in relative prices are the usual intervening mechanism in trade models. So in evaluating the impact of trade on labour markets, previous work has looked for evidence of an increase in the relative prices of skill-intensive goods (*e.g.* Lawrence and Slaughter, 1993). In this model, however, induced skill-biased technical change in the U.S. implies that trade may increase the price of skill-intensive goods by only a limited amount, or not at all, but may still have a major effect on the U.S. labour market. The inconclusive or paradoxical evidence reported in these papers on the behaviour of the relative prices of skill-intensive goods does not imply that trade is not a major driving force of the recent rise in inequality.

How large is the effect of trade opening on the skill premium for plausible parameter values? To answer this question, consider the estimate by Borjas *et al.* (1997) of $\ln(H^W/L^W) - \ln(H^U/L^U) \approx 0{\cdot}04$ between 1980 and 1995 used in Section 2. Now equations (26) and (35) imply that $\ln \hat{\omega} - \ln \omega^U = -[\ln(H^W/L^W) - \ln(H^U/L^U)]$, so we expect trade opening to increase the skill premium by approximately 4% between 1980 and 1995, which accounts for 20% of the actual increase ($4/20 \approx 20\%$), or makes trade twice as important as in models with exogenous technology. Given that some of the increase between 1980 and 1995 is likely to have been due to the slowdown in the supply of college graduates during the 1980's, this analysis implies that international trade could be an important component of the explanation for the increase in U.S. wage inequality.

4.2. *Intellectual property rights enforcement in the LDCs*

The previous subsection discussed the effect of international trade in a world without intellectual property rights enforcement in the LDCs. The next proposition generalizes this result to the case in which there is intellectual property rights enforcement, and is proved in the Appendix B:

Proposition 5. *Suppose that the world economy opens to international trade, and this change is unanticipated. Suppose moreover that* $\mu > 0$ *and* $\phi'(\cdot) < 0$.

(1) *There exists* $\mu^* > 0$, *such that if* $\mu < \mu^*$, *then after trade opening we have* $z_h > z_l$. *The skill bias of technology,* Q_h/Q_l, *unambiguously increases. The skill premium in the U.S. immediately jumps up after trade opening, then gradually increases further. The relative price of skill-intensive goods in the U.S. immediately increases, and then gradually declines.*
(2) *Suppose also that* $\eta < 0$, *than the above results hold for all* μ.

Therefore, most of the results are similar to those in Proposition 4.[20] But now international trade might affect the world growth rate, and the implications for the post-trade relative price of skill-intensive goods in the U.S. is ambiguous—that is, we could have $\hat{p}$ less than or greater than p^U.

5. CONCLUDING REMARKS AND FUTURE DIRECTIONS

This paper has constructed a simple model to analyse the patterns of skill premia we observe across countries and over time. Skill premia are determined by the relative supply of skills, the degree of skill bias in technology, and international trade. The major innovation of this framework is that skill bias of technology is endogenous, determined by the relative profitability of developing different types of technologies. An increase in the number of skilled workers expands the market size for skill-complementary technologies, and induces skill-biased technical change. This increase in the demand for skills implies that the long-run relative demand for skills can be upward sloping: skill premia may increase in response to a rise in the supply of skilled workers. The relationship between the relative supplies and skill premia across countries is quite different in nature, however: among countries with access to the same technology frontier, there will be a negative relationship between the relative supply of skills and the skill premium.

The most important results of the paper concern the effect of increased international trade on the U.S. labour market. I show that trade opening will cause skill-biased technical change in the U.S. In contrast with the standard models, this induced technology effect also implies that trade opening may increase skill premia in the LDCs, increase the demand for skills more significantly

20. Very different results would be obtained, however, if property rights were not enforced in LDCs before trade, and trade led to the full enforcement of these rights. In this case, the impact of trade (and the change in property rights enforcement regime) on the U.S. skill premium would be given by considering an increase in H/L in equation (24) in Section 3.

and more broadly than predicted by the standard calculations, and could have these implications without affecting the long-run relative price of skill-intensive goods.

One of the advantages of the framework presented here is its relative simplicity, enabling a number of extensions, with a variety of empirical implications. I conclude the paper with a brief discussion of some of these extensions.

5.1. *Trade and labour-biased technical change in Europe*

The analysis so far focused on a model in which there is one technological leader, the U.S. In reality, not only the U.S., but also a number of other advanced economies, such as European countries, develop frontier technologies. A natural conjecture may be that increased trade with the LDCs will also cause skill-biased technical change in Europe. However, in contrast to the U.S. experience, there has been little increase in inequality in continental Europe, and although the demand for skills has certainly increased in Europe over the past several decades, this increase appears to be somewhat less than in the U.S. (see Berman *et al.*, 1998). The framework presented here enables an analysis of this issue with some speculative and surprising results that can be empirically investigated in future work.

Suppose that "Europe" is relatively technologically advanced, in particular $q_s^U(i) > q_s^E(i) > \theta^E q_s^U(i)$ for $s = l, h$ and all i, where E denotes Europe. This implies that European firms will prefer to use technologies designed for their own needs rather than the U.S. ones, and there will be R&D in Europe, improving European technologies. Since the U.S. is more advanced than Europe, the LDCs continue to use U.S. technologies. Also assume that $H^U/L^U > H^E/L^E > H^j/L^j$ or all $j = 1, \ldots, J$.[21] Finally, to simplify the analysis I assume that Europe is small relative to the rest of the world economy.

The equations that describe technology choice in the U.S., in particular the equivalent of (24), now hold for Europe, so $Q_h^E/Q_l^E = ((1-\gamma)/\gamma)^\varepsilon (H^E/L^E)^{\beta(\varepsilon-1)}$. Differences in the relative supply of skills between the U.S. and Europe will imply different degrees of equilibrium skill bias in the two economies. In particular, since $H^U/L^U > H^E/L^E$, the U.S. will develop more skill-biased technologies than Europe. Also similarly, the skill premium in Europe will be $\omega^E = ((1-\gamma)/\gamma)^\varepsilon (H^E/L^E)^\eta$, where recall that $\eta \equiv \beta(\varepsilon - 1) - 1$. If the induced technology effect is strong enough, that is, if η is positive, the U.S. may have higher returns to skills despite its greater supply of skills.[22] This contrasts with the negative relationship between the supply of skills and skill premia among the set of countries with access to the same technology frontier (cf. Proposition 1). This result reflects the fact that differences in the relative supply of skills between the U.S. and Europe translate into differences in the technology frontiers of these economies.

Now suppose the world economy opens to trade, and hypothetically hold technologies fixed. Before trade, we have $p^U < p^E < p^j$ for $j \neq U, E$, so the relative price of skill-intensive goods is highest in the LDCs, next in Europe, and then in the U.S. Trade would lead to a new, common, relative price p^t.[23] It is clear that $p^j > p^t > p^U$, so the relative price of skill-intensive goods

21. Nickell and Bell (1996) argue that U.S. high school graduates are less skilled, so one might be tempted to think that supply of skills is not necessarily greater in the U.S. However, Devroye and Freeman (2000) show that there is no support for this presumption when comparing native born Americans with Europeans. All internationally comparable statistics, in turn, suggest that the fraction of workers with high education is greater in the U.S.

22. In practice, inequality and returns to schooling seem to be higher in the U.S. than in Europe, despite the greater supply of skills in the U.S. For example, in 1984, the log difference of the 90-th and 10-th deciles of the hourly wage distribution was 1·40 in the U.S., 1·16 in Britain, 1·23 in France, 1·01 in the Netherlands, 0·88 in Germany, 1·01 in Sweden and 1·04 in Japan (Freeman and Katz, 1995, Table 2). In the context of this framework, this pattern arises because the skill-abundant U.S. develops more skill-biased technologies than European countries.

The standard explanation for this pattern is institutional wage compression in Europe. The purpose of the exercise here is not to deny the importance of wage compression in Europe, but to offer a complementary explanation.

23. I am using p^t to distinguish this fixed technology case from the case where technology adjusts, $\hat{p}$.

would increase in the U.S. and would fall in the LDCs. The effect on Europe is ambiguous. It depends on the relative sizes of the U.S. and the LDCs, and the distance between Europe and these other countries. Let me assume that $p^t > p^E$, which is the reasonable case in practice. Therefore, in the absence of an induced change in technology, the impact of trade would be to increase the demand for skills in Europe.

Now consider trade opening in the world economy with endogenous technology. We know from Section 4 that the long-run equilibrium relative price of skill-intensive goods, denoted by $\hat{p}$, will have to adjust to satisfy the technology equilibrium condition (23) in the U.S. (this follows from the fact that LDCs still use U.S. technologies and Europe is relatively small). This implies that the technology equilibrium condition in Europe, which would have required $\hat{p} = (H^E/L^E)^{-\beta}$, will not be satisfied. In fact, we have

$$\hat{p} = p^U = (H^U/L^U)^{-\beta} < (H^E/L^E)^{-\beta} = p^E.$$

In other words, given the number of skilled workers in Europe, the world relative price of skill-intensive goods is too low for skilled innovations to be profitable there. European firms will therefore develop only labour-complementary technologies, and European skill-complementary technologies will stagnate. As a result, trade will *induce labour-biased technical change in Europe*, while causing skill-biased technical change in the U.S.[24] As U.S. skill-complementary technologies advance, it will eventually be profitable for European firms to begin using U.S. technologies in the skill-intensive sector, and skill-biased technical change will progress at the same rate in the two economies.

Therefore, this analysis provides an alternative explanation for why inequality did not increase in Europe. Implications of this analysis are testable with detailed product price data from Europe and the U.S. According to this approach, skill-intensive good prices should fall in Europe after trade opening, while they increase and then fall (or not change much) in the U.S. Interestingly, this is consistent with the results reported in Desjounqueres *et al.* (1999), which show a small increase in the relative price of skill-intensive goods in the U.S. and a decline in a number of European countries between 1974 and 1989.

5.2. *Trade and technology adoption*

The framework here predicts that opening to trade with the U.S. can increase skill premia and wage inequality in the LDCs. This follows from the effect of trade with the LDCs on U.S. product prices. If different LDCs were to open to U.S. trade at different times, the prediction of the framework would be more similar to the standard trade theory: to the extent that each individual LDC is small, its addition to the world trade system has a negligible effect on product prices in the U.S., and therefore a negligible effect on technology. So when an LDC opens for trade, holding trading patterns of other LDCs as given, it should experience a decline in wage inequality.[25] The

24. This result depends on the assumption that the U.S., Europe, and the LDCs all start trading with each other. It is of course possible that the world was characterized by free trade between the U.S. and Europe in the 1960's, and the big change was opening of trade between these countries and the LDCs. In that case, trade will cause skill-biased technical change in both the U.S. and Europe. However, the data suggest that trade between the U.S. and Europe grew at least as fast as trade between the U.S. and the LDCs (see, for example, World Bank, 1997).

Moreover, the results outlined here with goods produced by different countries as perfect substitutes, may appear somewhat extreme. The working paper version, Acemoglu (1999*b*), shows that the same results hold when different countries produce goods that are imperfectly substitutable.

25. In other words, this model suggests that the empirical relationship between the skill premium or inequality in country j and trade opening should be

$$\omega^j = a \cdot \text{ measure of trade opening in } j + b \cdot \text{ measure of trade opening in the U.S.},$$

with $a < 0$ and $b > 0$.

available evidence, discussed for example in footnote 6, suggests that trade opening does not lead to a decline in inequality, though this may result from other market reforms taking place concurrently.

The framework here suggests an alternative explanation. Notice that so far even without international trade, LDC firms copy U.S. technologies. A different plausible assumption is that LDC firms need to import some know-how and machines from U.S. technology firms in order to produce machines at home. Such machine imports may be harder or even impossible before opening to international trade. In that case, before trade countries would be using, at least to some degree, local technologies. These local technologies will be catered to their own needs. In particular, assuming that before trade opening, LDCs can only use local technologies, the analysis above implies that the pre-trade skill premium in country j is $\omega^j = \left(\frac{1-\gamma}{\gamma}\right)^{\varepsilon}\left(\frac{H^j}{L^j}\right)^{\eta}$. As a result, the technologies employed in the LDCs before trade will use less skill-biased than those in the U.S., because these countries are more abundant in unskilled workers relative to the U.S. However, provided that $\theta^j q_s^U(i) > q_s^j(i)$ for $s = l, h$ and all j and i, as we have assumed so far, when they can import machines, LDC firms will prefer to use U.S. technologies. After opening to trade, there will therefore be two changes: first, it is now the world supplies that matter for domestic prices; second, there will be a switch from domestic to U.S. technologies. Hence, the skill premium will now be given by $\hat{\omega} = \left[\left(\frac{1-\gamma}{\gamma}\right)^{-\varepsilon}\frac{H^W}{L^W}\right]^{-\frac{1}{2+\eta}}\left(\frac{Q_h^U}{Q_l^U}\right)^{\frac{1+\eta}{2+\eta}}$. This skill premium can be greater than ω^j, if U.S. technology is sufficiently more skill-biased than pre-trade local technologies, *i.e.* if $Q_h^U/Q_l^U \gg Q_h^j/Q_l^j$. More generally, we may expect little change in inequality when an LDC opens to trade, and a general increase in inequality in many of the LDCs over the period of global trade opening, which is consistent with the existing evidence.[26]

5.3. *Technology choices in the LDCs*

Another important extension is to endogenize the technology adoption decisions in the LDCs and the productivity of U.S. technologies when used in other countries. Imagine a generalization of the above framework where LDC technology firms have to perform R&D in order to copy and adopt U.S. technologies. In particular, suppose that local firms have to undertake R&D to develop machines that can be used in the LDCs (*i.e.* that are appropriate to the conditions in the LDCs). Nevertheless, the state of knowledge in the U.S. as captured by Q_l^U and Q_h^U, affects the relative costs of R&D in these countries. More specifically, assume that the cost of R&D on a machine for skill type s of quality q in LDC j is $B^j q(Q_s^U/Q_s^j)^{\zeta}$. The last term in this expression implies that the farther behind is a country relative to the U.S. in a given sector, the cheaper it is to develop technologies in that sector. From the analysis so far, it is straightforward to see that in the case without trade, the BGP condition in country j becomes $(p^j)^{1/\beta}(H^j/L^j) = (Q_h^U/Q_l^j)^{\zeta}(Q_l^U/Q_l^j)^{-\zeta}$. This expression incorporates the fact that the more skill-biased are U.S. technologies, the easier it is for LDCs to develop their own skill-biased technologies. The equilibrium skill bias in country j is then obtained as

$$\frac{Q_h^j}{Q_l^j} = \left(\frac{1-\gamma}{\gamma}\right)^{\frac{\varepsilon}{1-\zeta(2+\eta)}}\left(\frac{H^j}{L^j}\right)^{\frac{1+\eta}{1-\zeta(2+\eta)}}\left(\frac{Q_h^U}{Q_l^U}\right)^{\frac{\zeta(2+\eta)}{1-\zeta(2+\eta)}}.$$

An interesting implication of this expression is that now each country's relative supply of skills will affect its own technology, and countries with greater supply of skills will adopt more skill-

26. Freeman and Oostendorp (2000) and Behrman *et al.* (2001) find no change in inequality when an LDC opens up to trade, but a general increase in inequality in the LDCs over this period of global trade opening.

biased technologies and may have greater skill premia—as in the U.S.–Europe comparison in Section 5.1. But in addition, as in the basic model of Section 3, the U.S. skill bias will also affect LDC technology choices.

This model might shed some light on the patterns of diffusion of skill-biased technology. For example, Berman and Machin (2000) show that there has been rapid skill-upgrading in many middle income countries, but there is much less evidence of rapid skill-upgrading in the poorest economies. This may reflect differences in these countries' choices of whether to adopt the new skill-biased technologies developed in the U.S., which are in turn determined by the relative supply of skilled workers in these countries. More generally, a more detailed theoretical and empirical analysis of the interaction between technical change in the U.S. and technology adoption in LDCs, and its implications for the distribution of wages, appears to be a fruitful area for future research.

APPENDIX A. DATA

The samples are constructed as in Katz and Autor (1999). I thank David Autor for providing me with data from this study. Data from 1939, 1949 and 1959 come from 1940, 1950 and 1960 censuses. The rest of the data come from 1964–1997 March CPSs. The college premium is the coefficient on workers with a college degree or more relative to high school graduates in a log weekly wage regression. The regression also includes dummies for other education categories, a quartic in experience, three region dummies, a nonwhite dummy, a female dummy, and interactions between the female dummy and the nonwhite dummy and the experience controls. The sample includes all full-time full-year workers between the ages of 18 and 65, and except those with the lowest 1% earnings. Earnings for top coded observations are calculated as the value of the top code times 1·5. The relative supply of skills is calculated from a sample that includes all workers between the ages of 18 and 65. It is defined as the ratio of college equivalents to noncollege equivalents, calculated as in Autor *et al.* (1998) using weeks worked as weights. In particular, college equivalents = college graduates + 0·5 × workers with some college, and noncollege equivalents = high school dropouts + high school graduates + 0·5 × workers with some college.

APPENDIX B. PROOFS

Proof of Proposition 2. First note that $\bar{\pi}_s(\lambda q_s(i))/\lambda q_s(i)$ is independent of the level of machine quality, $q_s(i)$, out of BGP as well. Then, combining equations (20) and (21) implies that $z_s(q_s(i)) = z_s$. So we only have to determine the time path of z_h, z_l, Q_l and Q_h. (21) holds at all times, so differentiating it with respect to time and using (20), we obtain $\dot{z}_s = \frac{-\phi(z_s)\dot{V}_s}{\phi'(z_s)V_s} \equiv \frac{\dot{V}_s z_s}{\sigma_\phi(z_s)V_s}$ for $s = l, h$, where σ_ϕ is the elasticity of the ϕ function. Combining this with (20) and using (21), we obtain:

$$\dot{z}_h = \frac{r + z_h\phi(z_h) - \phi(z_h)(p_h^U)^{1/\beta}H^U}{\sigma_\phi(z_h)/z_h} \quad \text{and} \quad \dot{z}_l = \frac{r + z_l\phi(z_l) - \phi(z_l)(p_l^U)^{1/\beta}L^U}{\sigma_\phi(z_l)/z_l}. \tag{B.1}$$

Next note that $\dot{Q}_s/Q_s = (\lambda - 1)\phi(z_s)z_s$, so defining $Q \equiv Q_h/Q_l$

$$\dot{Q} = (\lambda - 1)(z_h\phi(z_h) - z_l\phi(z_l))Q. \tag{B.2}$$

Equations (B.1) and (B.2) completely describe the dynamics of the system. To analyse local dynamics and stability in the neighbourhood of the BGP, I linearize these equations. Then, around the BGP, $z_l = z_h = z^*$, $Q = Q^* \equiv ((1-\gamma)/\gamma)^\varepsilon (H^U/L^U)^{\beta(\varepsilon-1)}$, and ignoring constants, we have $\dot{z}_h = \frac{\sigma(z^*)(z_h - z^*)}{\sigma_\phi(z^*)/z^*} + \psi_1(z^*, Q^*)(Q - Q^*)$, $\dot{z}_l = \frac{\Delta(z^*)(z_l - z^*)}{\sigma_\phi(z^*)/z^*} - \psi_2(z^*, Q^*)(Q - Q^*)$ and $\dot{Q} = \Delta(z^*)Q^*(z_h - z_l)$, where $\Delta(z^*) \equiv \phi'(z^*)z^* + \phi(z^*) > 0$. ψ_1 and ψ_2 are analogously defined, and are both positive. This linearization enables us to reduce the three variable system to two variables Q and $\zeta \equiv z_h - z_l$:

$$\dot{Q} = \Delta(z^*)Q^*\zeta \quad \text{and} \quad \dot{\zeta} = \frac{\Delta(z^*)}{\sigma_\phi(z^*)/z^*}\zeta + \psi(z^*, Q^*)(Q - Q^*),$$

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.

In contrast when $\phi(\cdot) \equiv$ constant, there are no transitional dynamics, and the system immediately jumps to the BGP. That is, when $Q < Q^*$ we would have $z_l = 0$ and $z_h \to \infty$ for an infinitesimally short while, and we immediately jump to $Q = Q^*$. ||

Proof of Proposition 3. Let $\Delta\Pi(Q_h/Q_l) \equiv \bar{\pi}_h(\lambda q_h(i))/\lambda q_h(i) - \bar{\pi}_l(\lambda q_l(i))/\lambda q_l(i)$ where $\bar{\pi}_h$ and $\bar{\pi}_l$ are given by (28) and (29), and depend on Q_h/Q_l through the price terms. These price terms are given by

$$p_l^j = \left[\gamma + (1-\gamma)\left[\left(\frac{1-\gamma}{\gamma}\right)^{-\varepsilon} \frac{Q_h}{Q_l}\frac{H^j}{L^j}\right]^{\frac{\beta(\varepsilon-1)}{1+\beta(\varepsilon-1)}}\right]^{\frac{1}{\varepsilon-1}} \quad \text{and}$$

$$p_h^j = \left[\gamma\left[\left(\frac{1-\gamma}{\gamma}\right)^{-\varepsilon} \frac{Q_h}{Q_l}\frac{H^j}{L^j}\right]^{-\frac{\beta(\varepsilon-1)}{1+\beta(\varepsilon-1)}} + (1-\gamma)\right]^{\frac{1}{\varepsilon-1}},$$

which yields $\partial p_l^j/\partial(Q_h/Q_l) > 0$ and $\partial p_h^j/\partial(Q_h/Q_l) < 0$.

The result $\partial\Delta\Pi(Q_h/Q_l)/\partial(Q_h/Q_l) < 0$ immediately follows. Then, as explained in the text, $\partial(Q_h/Q_l)^e/\partial(H^U/L^U) \lesseqgtr 0$ if and only if $\partial\Delta\Pi/\partial(H^U/L^U) \lesseqgtr 0$ *i.e.* depending on whether the downward-sloping curve in Figure 4 shifts out or in, where I use the notation $(Q_h/Q_l)^e$ to denote the equilibrium value of Q_h/Q_l. Next note that

$$\frac{\partial\Delta\Pi}{\partial(H^U/L^U)} \propto \frac{\partial\left[(p_h^U)^{1/\beta}\frac{H^U}{L^U} - (p_l^U)^{1/\beta}\right]}{\partial(H^U/L^U)}.$$

Also $p_l^U = [\gamma + (1-\gamma)(p^U)^{\varepsilon-1}]^{1/(1-\varepsilon)}$ and we can write the price of the skill-intensive good as $p_h^U = [\gamma + (1-\gamma)(p^U)^{\varepsilon-1}]^{1/(1-\varepsilon)}p^U$, where p^U is given by (18). This then implies that

$$\frac{\partial\Delta\Pi}{\partial(H^U/L^U)} \propto \frac{\partial\left[(p_l^U)^{1/\beta}\left\{(p^U)^{1/\beta}\frac{H^U}{L^U} - 1\right\}\right]}{\partial(H^U/L^U)},$$

which gives

$$\frac{\partial\Delta\Pi}{\partial(H^U/L^U)} \propto -\frac{1}{\beta}(p_l^U)^{(1-\beta(1-\varepsilon))/\beta}L^U\left\{(p^U)^{1/\beta}\frac{H^U}{L^U} - 1\right\}\frac{\partial p^U}{\partial(H^U/L^U)}$$
$$+(p_l^U)^{1/\beta}(p^U)^{(1-\beta)/\beta}\left\{p^U + \frac{1}{\beta}\frac{H^U}{L^U}\frac{\partial p^U}{\partial(H^U/L^U)}\right\}.$$

Next, we can seen that both lines of this expression are positive, which will establish that $\partial\Delta\Pi/\partial(H^U/L^U) > 0$. To see this, first note that from (18) we have:

$$\frac{\partial p^U}{\partial(H^U/L^U)} = -\frac{\beta}{1+\beta(\varepsilon-1)}p^U\left(\frac{H^U}{L^U}\right)^{-1} < 0.$$

This and the fact that $\varepsilon > 1$ imply that

$$\frac{\partial((p^U)^{1/\beta}H^U/L^U)}{\partial(H^U/L^U)} \propto \left\{p^U + \frac{1}{\beta}\frac{H^U}{L^U}\frac{\partial p^U}{\partial(H^U/L^U)}\right\} = p^U\left[1 - \frac{1}{1+\beta(\varepsilon-1)}\right] > 0,$$

establishing that the second line is positive.

Furthermore, the same argument implies that $(p^j)^{1/\beta}\frac{H^j}{L^j}$ is increasing in $\frac{H^j}{L^j}$, and thus from the fact that $\frac{H^U}{L^U} > \frac{H^j}{L^j}$ for all $j > 0$, we have $(p^U)^{1/\beta}\frac{H^U}{L^U} > (p^j)^{1/\beta}\frac{H^j}{L^j}$ for all $j > 0$. This implies that we must also have $(p^U)^{1/\beta}\frac{H^U}{L^U} > 1$. To see this, note that in equilibrium we have $\Delta\Pi = 0$, which can be written as

$$\Delta\Pi = (p^U)^{1/\beta}\frac{H^U}{L^U} - 1 + \frac{\mu}{(p_l^U)^{1/\beta}L^U}\left(\sum_{j=1}^{J}\theta^j(p_l^j)^{1/\beta}L^j\left\{(p^j)^{1/\beta}\frac{H^j}{L_j} - 1\right\}\right) = 0.$$

Since, as shown above, $(p^U)^{1/\beta}\frac{H^U}{L^U} > (p^j)^{1/\beta}\frac{H^j}{L^j}$ for all $j > 0$, we must have $(p^U)^{1/\beta}\frac{H^U}{L^U} > 1$ (otherwise, we would necessarily have $\Delta\Pi < 0$). Together with the fact that $\partial p^U/\partial(H^U/L^U) < 0$, this establishes that the first line is positive. Therefore, $\partial\Delta\Pi/\partial(H^U/L^U) > 0$, and an increase in H^U/L^U causes an increase in $(Q_h/Q_l)^e$, *i.e.* skill-biased technical change.

Next, it is straightforward to check that $\partial\Delta\Pi/\partial\mu < 0$, which, by the same argument, implies $\partial(Q_h/Q_l)^e/\partial\mu < 0$. ||

Proof of Proposition 4. BGP results are proved in the text. To obtain the dynamics, first note that since the change is unanticipated, after trade opening the state variable Q_h/Q_l is unchanged. Equation (19) gives the world skill premium immediately after trade opening as $\bar{\omega}$, and implies that the relative price of skilled-intensive goods will be

$$p^j = \left(\frac{H^U}{L^U}\right)^{\beta\frac{1+\eta}{2+\eta}} \frac{H^W}{L^W}^{-\beta\frac{1}{2+\eta}} > p^U = \hat{p}.$$

So we only have to characterize the transitional dynamics after this initial change. To do this, simply use the argument from the proof of Proposition 2, with the only change that $Q^* = (\frac{1-\gamma}{\gamma})^{\varepsilon}\left(\frac{H^W}{L^W}\right)^{-1}\left(\frac{H^U}{L^U}\right)^{2+\eta}$. This establishes that the system is saddlepath stable, and will adjust gradually to the new BGP skill bias, Q^*, as long as $\phi' < 0$. Next note that the pre-trade skill bias, Q_h/Q_l, is less than Q^*, so the adjustment will feature $z_h > z_l$, a decline in the relative price of skill-intensive goods to $\hat{p} = p^U$, and an increase in the skill premium to $\hat{\omega}$. Finally, if $\phi' = 0$, the adjustment will be immediate. ||

Proof of Proposition 5. Let me define $\Delta^2\Pi$ as the difference in relative profitability of skill-biased technologies between the worlds with free trade and no trade. That is,

$$\Delta^2\Pi(\cdot \mid \mu) = \Delta\Pi(Q_h/Q_l \mid \text{free trade}) - \Delta\Pi(Q_h/Q_l \mid \text{no trade})$$

with $\Delta\Pi(Q_h/Q_l)$ defined by (30). If $\Delta^2\Pi > 0$, then trade opening increases the profitability of skill-biased technologies, and induces skill-biased technical change.

From the definition of (30), we have that

$$\Delta^2\Pi(\cdot \mid \mu) = \beta(1-\beta)\lambda \begin{bmatrix} ((\hat{p}_h)^{1/\beta} - (p_h^U)^{1/\beta})H^U + \mu\sum_j \theta^j((\hat{p}_h)^{1/\beta} - (p_h^j)^{1/\beta})H^j \\ -((\hat{p}_l)^{1/\beta} - (p_l^U)^{1/\beta})L^U - \mu\sum_j \theta^j((\hat{p}_l)^{1/\beta} - (p_l^j)^{1/\beta})L^j \end{bmatrix}.$$

By the assumption that the U.S. is more skill-intensive than the LDCs (in particular, equation (12)), we have

$$\hat{p}_h > p_h^U \quad \text{and} \quad \hat{p}_l < p_l^U; \quad \text{and} \quad \hat{p}_h < p_h^j \quad \text{and} \quad \hat{p}_l > p_l^j \quad \text{for all } j$$

so we immediately have that

$$\frac{\partial\Delta^2\Pi(\cdot \mid \mu)}{\partial\mu} < 0.$$

To prove the first part of the proposition, simply note that $\Delta^2\Pi(\cdot \mid \mu = 0) > 0$, so there exists at least some range where $[0, \mu^*)$ where $\Delta^2\Pi(\cdot \mid \mu) > 0$ for all $\mu \in [0, \mu^*)$. The transitional dynamics after trade opening then follow with an identical argument to that in the proof of Proposition 4.

To prove the second part, note that if $\Delta^2\Pi(\cdot \mid \mu = 1) > 0$, than a *fortiori* $\Delta^2\Pi(\cdot \mid \mu) > 0$ for all $\mu \leq 1$. To show that $\Delta^2\Pi(\cdot \mid \mu = 1) > 0$ for $\eta < 0$, note that when $\mu = 1$, we have

$$\Delta\Pi\left(\left\{\frac{H^j}{L^j}\right\}_{j=0}^{J}, \frac{Q_h}{Q_l} \mid \text{no trade}\right) = \sum\nolimits_{j=0}^{J} \theta^j L^j \delta\left(\frac{H^j}{L^j}, \frac{Q_h}{Q_l}\right) \tag{B.3}$$

where

$$\delta\left(\frac{H}{L}, \frac{Q_h}{Q_l}\right) \equiv \left[\gamma^{\varepsilon} + (1-\gamma)^{\varepsilon}\left[\left(\frac{1-\gamma}{\gamma}\right)^{-\varepsilon}\frac{Q_h}{Q_l}\frac{H}{L}\right]^{-\frac{\beta(\varepsilon-1)}{1+\beta(\varepsilon-1)}}\right]^{\frac{1}{\beta(\varepsilon-1)}}\left\{\frac{H}{L} - 1\right\} \tag{B.4}$$

with the convention that $j = 0$ corresponds to the U.S. and $\theta^0 = 1$. In addition, we have

$$\Delta\Pi\left(\frac{H^W}{L^W}, \frac{Q_h}{Q_l} \mid \text{free trade}\right) = \sum\nolimits_{j=0}^{J} \theta^j L^j \delta\left(\frac{H^W}{L^W}, \frac{Q_h}{Q_l}\right), \tag{B.5}$$

where

$$\frac{H^W}{L^W} = \frac{\sum_{j=0}^{J} \theta^j H^j}{\sum_{j=0}^{J} \theta^j L^j}.$$

Now without loss of any generality, normalize $\sum_{j=0}^{J} \theta^j L^j = 1$. This implies that H^W/L^W is the weighted mean of H^j/L^j with each observation weighted by $\theta^j L^j$. Thus, the move from free trade to no trade can be thought of a "mean preserving spread" of the distribution $\{H^j/L^j\}_{j=0}^{J}$. Hence to show that (B.5) is greater than (B.3) it is sufficient to show that $\delta(H/L, Q_h/Q_l)$ is concave in H/L. Differentiating (B.4) twice and some algebra show that it is strictly concave for $\eta < 0$ and $H/L < ((1-\gamma)/\gamma)^{-\varepsilon/\eta}$ in all countries, in particular, in the U.S. (which is necessary to ensure a positive skill premium, recall footnote 16). ||

APPENDIX C. THE RESPONSE OF THE SUPPLY OF SKILLS

Consider the following extension of the model. In each country, a continuum υ of unskilled agents are born every period, and each faces a flow rate of death equal to υ, so that the population is constant at 1 (as in Blanchard, 1985). Each agent chooses upon birth whether to acquire the education required to become a skilled worker. It takes T_x periods for agent x to become skilled, and during this time, he earns no labour income. The distribution of T_x is given by the function $G^j(T)$ in country j. The distribution of T is the only source of heterogeneity in this economy, and may be due to credit market imperfections, differences in innate ability, or government policy towards education. The rest of the set-up is unchanged. To simplify the exposition, I assume that $G^j(T)$ has no mass points, and consider the case with no property rights enforcement in the LDCs, *i.e.* $\mu = 0$.

A BGP is now defined as an equilibrium in which H^j/L^j and the skill premium ω^j remain constant in all countries. In BGP, there is a single-crossing property: if an individual with cost of education T_x chooses schooling in country j, then all agents with $T_{x'} < T_x$ in country j must also prefer to acquire skills. Therefore, there exists a cutoff level of talent, $\bar{T}^j$, such that all $T_x > \bar{T}^j$ in country j do not acquire education. Assume that we are near BGP and υ is small, then:[27]

$$\frac{H^j}{L^j} \approx \frac{G^j(\bar{T}^j)}{1 - G^j(\bar{T}^j)}. \tag{C.1}$$

Next we need to determine the cutoff level $\bar{T}^j$. The agent with talent $\bar{T}^j$ in country j needs to be indifferent between acquiring skills and not. When he does not acquire any skills, his return at time t is $R_{ne}^j = \int_t^\infty \exp[-(r+\upsilon)(\tau - t)] w_l^j(\tau) d\tau = w_l^j \int_0^\infty \exp[-(r+\upsilon-g)\tau] d\tau = w_l^j (r+\upsilon-g)$ where $r+\upsilon$ is the effective discount rate, w_l^j is the unskilled wage in country j, and I have used the fact that along the BGP, wages in all countries grow at the constant growth rate g. If in contrast the agent with $\bar{T}^j$ decides to acquire education, he receives nothing for a segment of time of length $\bar{T}^j$, and receives the skilled wage thereafter. Therefore, the return to agent $\bar{T}^j$ from acquiring education, $R_e^j(\bar{T}^j)$, can be written as $R_e^j(\bar{T}^j) = \int_{t+\bar{T}^j}^\infty \exp[-(r+\upsilon)(\tau - t)] w_h^j(\tau) d\tau = \exp[-(r+\upsilon-g)\bar{T}^j] w_h^j/(r+\upsilon-g)$. In BGP, for $\bar{T}^j$ to be indifferent, we need $R_e^j(\bar{T}^j) = R_{ne}^j$ at all times, so in country j, $\omega^j \equiv w_h^j/w_l^j = \exp[(r+\upsilon-g)\bar{T}^j]$. Inverting this equation and substituting into (C.1), we obtain the relative supply of skills as a function of the skill premium

$$\frac{H^j}{L^j} \approx \frac{G^j(\ln(\omega^j)/(r+\upsilon-g))}{1 - G^j(\ln(\omega^j)/(r+\upsilon-g))}. \tag{C.2}$$

The equilibrium of each country $j \neq U$ is given by the intersection of the relative supply (C.2) with the relative demand for skills given by (19) above for a given skill bias of technology, Q_h/Q_l. The skill bias is in turn determined from equation (24), but the U.S. relative supply of skills, H^U/L^U, is also endogenous. When $\eta > 0$, so that the long-run relative demand for skills is upward sloping, multiple equilibria are possible. Figure C.1 shows this case diagrammatically. In one equilibrium, the relative supply of skills is high, which makes technology more skill-biased, increasing the skill premium, and encouraging more investment in skills. In the other equilibrium, the skill premium is low, so relatively few agents acquire skills, this encourages the development of less skill-biased technologies and supports a low skill premium.

It is also clear from this framework that the only reason why the supply of skills will differ between countries is because of the function G^j. As before, the plausible case is the one in which there is a greater supply of skills in the U.S. than in the LDCs. This corresponds to G^U being first-order stochastically dominated by G^j's, *i.e.* G^U has more weight at shorter duration of required schooling than the G^j's. There could be a number of reasons for this difference in the

27. This is only an approximation because it does not take into account the agents who have chosen to acquire skills, and are in the process of doing so. As $\upsilon \to 0$, this expression becomes exact.

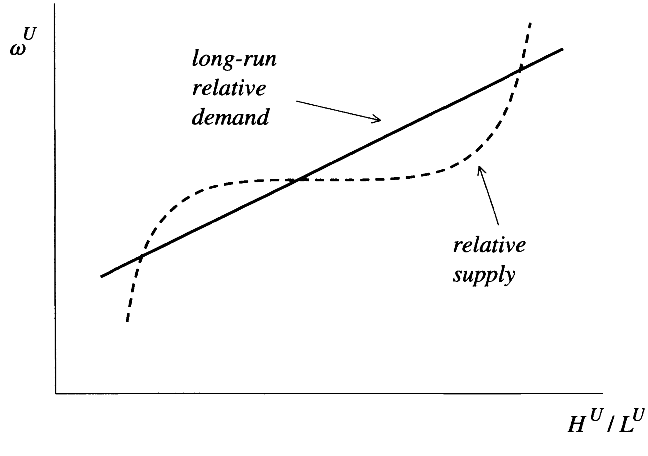

FIGURE C.1

Determination of equilibrium skill bias and relative supply of skills in the U.S. with $\eta > 0$

propensity to invest in skills (*i.e.* for the differences in G's). Government subsidies for education are more extensive in the U.S., reducing the costs of education as captured by G, and individuals have better access to credit and typically have longer life expectancy. All these factors make individuals in the U.S. more likely to invest in skills than in the LDCs.

This analysis also provides an interesting way to think about the developments in the U.S. labour market over the past 60 years or even during the past century. As Figure 1 shows, there is a large increase in the supply of skills accompanied by an increase in the skill premium, most likely due to secular skill-biased technical change. How do we make sense of this pattern? Consider the model developed here, and suppose that H^U/L^U starts below its steady state level. Moreover, suppose that $\phi'(z) = 0$. In this case, it is straightforward to show that the economy will converge to the BGP with H^U/L^U and Q_h/Q_l increasing steadily. Furthermore, if $\eta > 0$, the skill premium will increase over this process.

Finally, consider a shift to the left in the function G^U in the U.S., which will increase H^U/L^U. The analysis so far establishes that this increase in the relative supply of skilled workers will increase the skill bias of technology Q_h/Q_l. This change in technology will unambiguously increase the skill premium at a given relative supply of skills in all LDCs, and therefore encourage more investment in skills in these countries.

It is also straightforward to repeat this analysis for the case with international trade. The most important result is that because international trade will cause skill-biased technical change and increase the skill premium in the U.S., it will also encourage further skill accumulation. This implies that there will be yet one more force towards more skill-biased technical change, since the increase in H^U/L^U (resulting from trade opening) will encourage further skill-biased technical change.

As emphasized in the text, trade opening may increase or decrease the skill premium in an LDC. In those countries where skilled premia increase, there will be further investment in education, and when the skill premium decreases, there might be less investment in education. Therefore, the implications of trade opening for investment in skills in the LDCs is ambiguous.

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