Endogenous Technology Bias, International Trade, and Relative Wages

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Abstract

We endogenize factor bias and sector bias of technical progress in the 2x2x2 Heckscher-Ohlin framework. International trade affects technology biases by changing the incentive for innovating technologies that complement different factors and sectors. We use the model to investigate the relative-wage effects of trade in final goods, intermediate goods, and technologies, between two countries who both innovate, and between one country who innovates and one country who imitates. Our investigation identifies conditions for the model to explain observed rising wage inequality in developed and less developed countries in recent decades.

Key words: Heckscher-Ohlin; Endogenous technology; Factor bias; Sector bias; Wage inequality

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1 Introduction

The recent literature on wage inequality has used the Heckscher-Ohlin (HO) model as the main theoretical framework. This model shows the general-equilibrium linkages between international trade, technical progress, and relative wages. The effects of trade on relative factor prices are summarized in the Stolper-Samuelson (1941) theorem, and the effects of technical progress on relative factor prices are shown in Findlay and Grubert (1959) and Jones (1965). Recently, Jones (2000), Krugman (2000), and Xu (2001) have provided further elaboration of the relationship between technical progress and relative factor prices in the HO model.

A shortcoming of the HO model is that it treats technology as either constant or changing exogenously. Although Grossman and Helpman (1991) endogenized the *rate* of technical progress in the HO framework, they did not endogenize the *bias* of technical progress. The recent literature on wage inequality demonstrates that it is the factor bias and sector bias of technical progress that determine how technology affects relative wages.

The possibility of technology bias being endogenous was noted in Hicks (1932), who wrote: "A change in the relative prices of the factors of production is itself a spur to invention, and to invention of a particular kind — directed to economising the use of a factor which has become relatively expensive ... We need to distinguish two sorts of inventions. We must put on one side those inventions which are the result of a change in the relative prices of the factors; let us call these 'induced' inventions. The rest we may call 'autonomous' inventions." (pp. 124-125) A literature in the 1960s attempted to formalize the idea of Hicks. Models in that literature (e.g., Kennedy, 1964; Samuelson, 1965) postulate an innovation possibility frontier that describes a trade-off between innovational reductions in labor versus capital requirements in production. An increase in wage rates relative to profit rates is shown to induce labor-saving technical progress. The main problem with this literature is its lack of micro-foundation of innovative behavior. The theory is also at odds with the current wage debate: it would predict *skill-saving* technical progress to be induced by the increase in the relative wage of skilled workers.

Recently, important progress has been made in modeling endogenous bias of technical change. Acemoglu (1998) builds a quality ladder model similar to that of Aghion and Howitt (1992) and Grossman and Helpman (1991), but allows the pace of skill-complementary and labor-complementary technologies to differ. In his model, skilled workers and unskilled workers use different technologies to produce a skill-using intermediate good and a labor-using intermediate good, which are then assembled into a final good. The relative magnitude of innovations in the two types of technologies determines the direction of technical progress. If more innovations occur in skill-complementary technologies than in labor-complementary technologies, then there will be skill-biased (i.e. labor-saving) technical progress. In the same spirit, Kiley (1999) builds a variety expanding model to endogenize the factor bias of technical progress. In his model, skill-complementary and labor-complementary intermediate goods are assembled into a final good. If the variety of skill-complementary intermediate goods expands faster than the variety of the labor-complementary intermediate goods, then there will be skill-biased technical progress.

At the heart of the recent models of endogenous technology bias is a market size effect: the incentive to innovate a technology depends on its number of users. A country's skill abundance measures the market size of skill-complementary technologies relative to that of labor-complementary technologies. Hence, as Acemoglu (1998) and Kiley (1999) show, more skill-biased technologies will be developed when the relative supply of skilled labor increases. The authors use this theory to explain rising wage inequality in the United States during the 1980s as a result of the rapid increase in the supply of college educated labor in the United States during the 1970s.

That technology bias is determined by factor abundance leads naturally to the question of how international trade, which is driven by differences in factor abundance according to the HO theory, affects technology bias. Acemoglu (1998, section V) presents a brief analysis of this issue and Acemoglu (1999) expands the analysis. In his model of one final good and two intermediate goods, Acemoglu examines trade in intermediate goods between the skill-abundant country (North) and the labor-abundant country (South). Assuming that the North innovates technologies which immediately diffuse to the South, he finds that the effects of trade opening on technology bias depend critically on the degree to which the South protects intellectual property rights (IPRs) of Northern innovators. If the South provides full IPR protection, then trade opening implies an increase in the relative market size of labor-complementary technologies for Northern innovators, which leads to labor-biased technical progress. However, if the South provides no IPR protection, then the market size for Northern innovators remains unchanged after trade opening. In this case, trade opening, by increasing the price of the skill-using intermediate good in the North, leads to skill-biased technical progress.

The studies of Acemoglu (1998, 1999) offer important insights into the impact of trade on technology bias. However, his model is designed for a closed economy analysis and is limited in structure for a comprehensive analysis of international trade. In his model, a final good is produced from two intermediate goods. One intermediate good is produced solely by unskilled workers with labor-complementary technology, and the other intermediate good is produced solely by skilled workers using skill-complementary technology. Thus the production structure contains essentially one final good produced from unskilled and skilled labor with factor-augmenting technologies. To discuss trade issues, Acemoglu introduces trade in intermediate goods. If we reinterpret Acemoglu's two intermediate goods as two final goods and the production function of his final good as a utility function, then the Acemoglu model has a 2x2 structure of a trade model, but a unique one because the two goods are produced using either unskilled labor or skilled labor as inputs. Although this structure provides a shortcut to showing the effects of trade on factor bias of technical progress, it abstracts away a number of important issues, which can only be addressed in a more general framework.

In this paper we use the 2x2x2 HO model as the analytical framework. Two final goods are produced from unskilled and skilled labor. We follow Acemoglu (1998) to determine factor bias of technical progress as a function of factor abundance and relative commodity prices, and extend his approach to determine sector bias of technical progress as a function of relative factor employment in the two sectors. The model allows us to address a number of issues not analyzed in Acemoglu (1998, 1999). First, how does the endogeneity of technical progress affect the pattern of trade? In Acemoglu (1998, 1999), countries trade a "labor" good and a "skill" good and hence skill abundance directly implies trade patterns. When production functions are more general, however, it is not immediately clear whether the skill-abundant country will have a comparative advantage in the skill-intensive good, given that skill abundance also affects technologies. We identify the conditions for the Heckscher-Ohlin theorem to hold when technical progress is endogenous.

Second, how does opening to trade affect sector bias of technical progress? The Acemoglu model endogenizes factor bias of technical progress. We will show that international trade necessarily causes technologies in the two sectors to change at different rates. As is well-known in the recent trade-wages literature, the sector bias of technical progress plays a key role in the relationship between trade opening and wage inequality (Leamer, 1998; Krugman, 2000; Xu, 2001). Thus, it is important to examine the effect of international trade on wage inequality in a model with endogenous sector bias of technical progress.

Third, how does Northern skill supply impact wage inequality in the South? In Acemoglu (1998, 1999), an increase in the skill supply of the North results in skill-biased technical progress in the South (who uses Northern technologies) and raises wage inequality there. We show that an increase in Northern skill supply induces technical progress not only biased toward skilled labor but also biased toward the skill-intensive sector. This finding is important because for small open Southern economies, it is the sector bias rather than the factor bias of technical progress that determines relative wages.

The remainder of the paper is organized as follows. In section 2 we specify a 2x2 HO model with factor-augmenting technology parameters and endogenize these parameters in a quality ladder model. In section 3 we solve the autarky general equilibrium. In section 4 we examine the effects of trade opening between two countries that differ only in skill abundance. In section 5 we examine the effects of trade opening between the North who innovates and the South who imitates. In section 6 we conclude.

2 The Model

2.1 A Heckscher-Ohlin Economy with Technology Parameters

We first describe a two-by-two Heckscher-Ohlin economy with exogenous technology parameters. This economy produces two final goods, X and Y, from two production factors, H and L. We specify the following CES production functions:[1]

$$X = [(A_x L_x)^\rho + (B_x H_x)^\rho]^{\frac{1}{\rho}}, \tag{1}$$

$$Y = [(A_y L_y)^\rho + (B_y H_y)^\rho]^{\frac{1}{\rho}}, \tag{2}$$

where L_i and H_i denote unskilled labor (henceforth labor) and skilled labor (henceforth skill) employed in sector i, A_i and B_i are labor-augmenting and skill-augmenting technology parameters of sector i, and $\rho \leq 1$ is a parameter associated with the elasticity of factor substitution, $\sigma \equiv 1/(1-\rho)$.[2] Denote w_l and w_h as wages for unskilled and skilled workers. The CES production functions imply the following CES unit cost functions (Varian, 1992, p. 56):

$$c_x = [(\frac{w_l}{A_x})^{1-\sigma} + (\frac{w_h}{B_x})^{1-\sigma}]^{\frac{1}{1-\sigma}}, \tag{3}$$

$$c_y = [(\frac{w_l}{A_y})^{1-\sigma} + (\frac{w_h}{B_y})^{1-\sigma}]^{\frac{1}{1-\sigma}}. \tag{4}$$

From (3) and (4) we obtain the skill intensities of the two sectors,

$$h_x \equiv \frac{\partial c_x/\partial w_h}{\partial c_x/\partial w_l} = \omega^{-\sigma}\beta_x^{\sigma-1}, \tag{5}$$

[1]The CES production function has the advantage of allowing an explicit expression for the elasticity of factor substitution, a key variable in our analysis. The model may be generalized to all linear homogeneous production functions, as Xu (2001) did for the Heckscher-Ohlin model with exogenous technology parameters.

[2]The elasticity of factor substitution is assumed to be the same in the two sectors.

$$h_y \equiv \frac{\partial c_y/\partial w_h}{\partial c_y/\partial w_l} = \omega^{-\sigma}\beta_y^{\sigma-1}, \tag{6}$$

where $\omega \equiv w_h/w_l$ and $\beta_i \equiv B_i/A_i$ for sector i. Equations (5) and (6) define factor bias of technical progress in the two sectors. According to Hicks (1932), technical progress is labor-saving (i.e. skill-biased) if it raises h_i at constant ω. Thus, an increase in β_i indicates skill-biased technical progress in sector i under the condition $\sigma > 1$. In this paper we will focus on the case of $\sigma > 1$.[3] As Acemoglu (1998) points out, most empirical studies yield an estimate of σ greater than one. Without loss of generality we assume that $\beta_x > \beta_y$, which implies that good X is more skill-intensive than good Y.

The markets for final goods are perfectly competitive. We choose good Y as the numéraire and denote p as the price of good X. Given that the country produces both goods,[4] we have the following zero-profit conditions:

$$c_x \equiv \frac{w_l}{A_x}(1+\omega h_x)^{\frac{1}{1-\sigma}} = p, \tag{7}$$

$$c_y \equiv \frac{w_l}{A_y}(1+\omega h_y)^{\frac{1}{1-\sigma}} = 1. \tag{8}$$

Equations (7) and (8) imply

$$\frac{A_y}{A_x}\left(\frac{1+\omega h_x}{1+\omega h_y}\right)^{\frac{1}{1-\sigma}} = p. \tag{9}$$

Turning to factor markets, we assume inelastic factor supplies and perfect competition, which lead to the following full-employment conditions:[5]

$$\frac{h_x}{A_x}(1+\omega h_x)^{\frac{\sigma}{1-\sigma}}X + \frac{h_y}{A_y}(1+\omega h_y)^{\frac{\sigma}{1-\sigma}}Y = H, \tag{10}$$

$$\frac{1}{A_x}(1+\omega h_x)^{\frac{\sigma}{1-\sigma}}X + \frac{1}{A_y}(1+\omega h_y)^{\frac{\sigma}{1-\sigma}}Y = L. \tag{11}$$

[3] Of course our model may be used to examine the case of $\sigma < 1$ in which an increase in β_i indicates *labor*-biased technical progress in sector i.

[4] This is true for a closed economy. However, in the presence of international trade, this requires countries to have similar technology-adjusted factor abundance.

[5] Unit factor requirement is obtained by partially differentiating the unit cost function with respect to the factor price.

Defining $h \equiv H/L$ and using (5) and (6), we obtain from (10) and (11):

$$\frac{X}{Y} = \frac{A_x(h - h_y)}{A_y(h_x - h)} \left(\frac{1 + \omega h_y}{1 + \omega h_x}\right)^{\frac{\sigma}{1-\sigma}}. \tag{12}$$

Turning to the demand side, we assume Cobb-Douglas preferences.[6] Let λ be the expenditure share on good X. The autarky equilibrium in goods markets implies

$$\frac{pX}{Y} = \frac{\lambda}{1 - \lambda}. \tag{13}$$

Substituting (9) and (12) into (13), using (5) and (6), we have

$$\frac{(h - \omega^{-\sigma}\beta_y^{\sigma-1})(1 + \omega^{1-\sigma}\beta_x^{\sigma-1})}{(\omega^{-\sigma}\beta_x^{\sigma-1} - h)(1 + \omega^{1-\sigma}\beta_y^{\sigma-1})} = \frac{\lambda}{1 - \lambda}. \tag{14}$$

Totally differentiating (14) yields relations between exogenous technical progress and relative wages. Xu (2001) derived the relations for both Cobb-Douglas and non-Cobb-Douglas preferences. An interesting finding for the Cobb-Douglas case is that the effect of technical progress on relative wages depends on factor bias but not on sector bias. That is, ω rises if technical progress is skill-biased (i.e. an increase in β_x or β_y under $\sigma > 1$) and ω falls if technical progress is labor-biased (i.e. a decrease in β_x or β_y under $\sigma > 1$), irrespective of which sector technology progresses faster. The sector bias of technical progress would matter for relative wages if preferences are non-Cobb-Douglas or if the country is a small open economy.

2.2 Endogenous Determination of Technology Biases

We now use the approach of Acemoglu (1998) to endogenize the determination of β_x and β_y. This approach adopts the view that technical progress improves quality of machines. Acemoglu (1998) assumes that machines either complement unskilled labor or skilled labor; this assumption allows him to determine the factor bias of technical progress as a result of relative quality improvements

[6] Assuming Cobb-Douglas preferences simplifies the analysis by abstracting away an indirect relative-wage effect of technical progress through expenditure shares. See Krugman (2000) and Xu (2001) for an examination of this indirect effect in the Heckscher-Ohlin model.

in the two types of machines. In our analysis we consider both factor bias and sector bias of technical progress, i.e., we allow β_x and β_y to change at different rates. Indeed, as we will show below, a sector bias of technical progress is necessary for both goods to be produced in the steady state equilibrium. Thus, for our purpose, we assume three types of machines: (1) machines that complement unskilled workers, (2) machines that complement skilled workers in sector X, and (3) machines that complement skilled workers in sector Y. Let M_l, M_x, and M_y be the quantity of machines used by unskilled workers, skilled workers in sector X, and skilled workers in sector Y, respectively, and q_l, q_x, and q_y be the quality of machines of the respective type. Following the literature we assume a continuum of machines for each type indexed by $j \in [0, 1]$; this simplifies the model by making technical progress deterministic and continuous. We also assume that machines depreciate fully after use to simplify the analysis.

Following Acemoglu (1998) we view final goods to be produced in two steps. First, workers use machines to produce intermediate goods. Second, intermediate goods assemble into final goods. Let Z_l be the intermediate good produced by unskilled workers using machine M_l, and Z_x and Z_y be the intermediate good produced by skilled workers using machines M_x and M_y, respectively. The production functions of the final goods are now given by $X = (Z_l^\rho + Z_x^\rho)^{\frac{1}{\rho}}$ and $Y = (Z_l^\rho + Z_y^\rho)^{\frac{1}{\rho}}$, and the production functions of the intermediate goods are given by[7]

$$Z_l = AL, \qquad Z_x = B_x H_x, \qquad Z_y = B_y H_y, \tag{15}$$

where the productivity of workers depends on the quality of machines and the quantity of machines per worker,

$$A = \frac{1}{1-\alpha} \int_0^1 q_l(j) \left(\frac{M_l(j)}{L} \right)^{1-\alpha} dj, \tag{16}$$

$$B_x = \frac{1}{1-\alpha} \int_0^1 q_x(j) \left(\frac{M_x(j)}{H_x} \right)^{1-\alpha} dj, \tag{17}$$

$$B_y = \frac{1}{1-\alpha} \int_0^1 q_y(j) \left(\frac{M_y(j)}{H_y} \right)^{1-\alpha} dj, \tag{18}$$

[7]Since we assume that unskilled workers operate the same type of machines, $A_x = A_y = A$.

where $0 < \alpha < 1$, and $q_s(j)$ is the highest quality of machine j of type s. The above specifications imply constant returns to scale in the production of intermediate goods; hence the number of firms in each intermediate-good sector is indeterminate.

Consider firm i in the intermediate-good sector that produces Z_l. The firm employs $L(i)$ units of unskilled labor and $M_l(i,j)$ units of the labor-complementary machine M_l of variety j. Let p_l be the price of the intermediate good Z_l, and $\xi_l(j)$ be the price of machine $M_l(j)$ of quality $q_l(j)$. The firm solves the following profit-maximization problem:

$$\underset{L(i),M_l(i,j)}{\text{Max}}\; p_l A(i) L(i) - \int_0^1 \xi_l(j) M_l(i,j) dj - w_l L(i). \tag{19}$$

The first-order conditions are given by

$$p_l \alpha A(i) = w_l, \tag{20}$$

$$p_l q_l(j) L(i)^{\alpha} M_l(i,j)^{-\alpha} = \xi_l(j). \tag{21}$$

Equations (20) indicates that $A(i) = A$ for all i. The two first-order conditions imply

$$M_l(i,j) = \left[\frac{q_l(j) w_l}{\alpha A \xi_l(j)}\right]^{\frac{1}{\alpha}} L(i). \tag{22}$$

Aggregating over all i we obtain the total demand for machine $M_l(j)$ as

$$M_l(j) = \left[\frac{q_l(j) w_l}{\alpha A \xi_l(j)}\right]^{\frac{1}{\alpha}} L. \tag{23}$$

An innovation increases the quality of the targeted machine by a factor $\mu > 1$. Innovation arrives randomly with a Poisson arrival rate γ, where γ is the amount of final goods used in R&D.[8] The innovator obtains a monopoly right over the vintage until replaced by the next innovator. To maximize profits, the innovator sets the price of the vintage to equate marginal revenue and marginal cost. The marginal revenue from owning machine $M_l(j)$ equals $(1 -$

[8] We assume that the share of good X in R&D expenditure is λ so that R&D activity has no effect on the relative commodity price and hence the relative wage of skilled labor.

$\alpha)\xi_l(j)$.[9] We assume that the marginal cost of inventing a machine increases linearly in its quality and normalize it to be $q_l(j)$ for machine $M_l(j)$. Equating the marginal revenue and the marginal cost leads to the following mark-up pricing equation:[10]

$$\xi_l(j) = \frac{q_l(j)}{1-\alpha}. \tag{24}$$

Substituting (24) into (23) we have

$$M_l(j) = \left[\frac{(1-\alpha)w_l}{\alpha A}\right]^{\frac{1}{\alpha}} L. \tag{25}$$

Equation (25) implies that $M_l(j) = M_l$ for all j.

Entry into the R&D sector is unrestricted. Denoting $V_l(j)$ as the stock market value of invention $M_l(j)$, the free-entry condition is given by

$$V_l(j) = q_l(j). \tag{26}$$

The left-hand side of (26) is the marginal return to R&D directed to the machine $M_l(j)$, and the right-hand side is the marginal cost of R&D.

The stock market value of an invention must meet a no-arbitrage condition. If an individual holds stock in the R&D firm that owns the current invention of $M_l(j)$, she receives a profit flow $\pi_l(j)$. However, her stock loses value when a new invention arrives. With $\gamma_l(j)$ being the flow of R&D input directed towards machine $M_l(j)$, a new invention arrives with the probability $\gamma_l(j)$. Alternatively, if the individual holds a well-diversified portfolio of stocks of different firms, she earns a safe return at the rate r.[11] The no-arbitrage condition requires that these two investment

[9] From (23) we obtain an expression for $\xi_j(j)$. Multiplying $\xi_l(j)$ and $M_l(j)$ yields an expression for total revenue. Partially differentiating total revenue with respect to $M_l(j)$ yields marginal revenue, which equals $(1-\alpha)\xi_l(j)$.

[10] There is a possibility that the intermediate-good producer may prefer the machine of the next best quality. To exclude this possibility, we assume $\mu > (1-\alpha)^{-\frac{1-\alpha}{\alpha}}$. Given this parameter restriction, intermediate-good firms would prefer the best quality machine even if the next best machine is sold at marginal cost. See Acemoglu (1998) for a discussion of this parameter restriction.

[11] All individuals share the intertemporal utility function $U(t) = \int_t^\infty e^{-r(\tau-t)}[\lambda \log C_x(\tau) + (1-\lambda)\log C_y(\tau)]d\tau$, where C_x and C_y are consumptions of goods X and Y, and r is the rate of time preference and is also the interest rate in the long-run equilibrium (Grossman and Helpman, 1991, p. 180).

choices yield the same expected return,

$$rV_l(j) = \pi_l(j) - \gamma_l(j)V_l(j) + \dot{V}_l(j), \tag{27}$$

where $\dot{V}_l(j)$ is the time derivative of $V_l(j)$. In the steady state, $\dot{V}_l(j) = 0$. By substituting (25) and (26) into (27), we find that $\gamma_l(j)$ is the same for all j and is given by[12]

$$\gamma_l = \left(\frac{1-\alpha}{\alpha}\right)^{\frac{1-\alpha}{\alpha}} \left(\frac{w_l}{A}\right)^{\frac{1}{\alpha}} L - r. \tag{28}$$

Following the same procedure, we obtain

$$\gamma_x = \left(\frac{1-\alpha}{\alpha}\right)^{\frac{1-\alpha}{\alpha}} \left(\frac{w_h}{B_x}\right)^{\frac{1}{\alpha}} H_x - r, \tag{29}$$

$$\gamma_y = \left(\frac{1-\alpha}{\alpha}\right)^{\frac{1-\alpha}{\alpha}} \left(\frac{w_h}{B_y}\right)^{\frac{1}{\alpha}} H_y - r, \tag{30}$$

where γ_x and γ_y denote total R&D directed to skill-complementary machines used in sectors X and Y, respectively. Recall that an innovation improves quality of a machine by $\mu > 1$. With a continuum of machines, the quality of machines of type s grows at a deterministic rate $(\mu - 1)\gamma_s$. In the balanced growth path, $\gamma_s = \gamma$ for all s.[13] Therefore, equations (28)-(30) imply

$$\left(\frac{w_l}{A}\right)^{\frac{1}{\alpha}} L = \left(\frac{w_h}{B_x}\right)^{\frac{1}{\alpha}} H_x = \left(\frac{w_h}{B_y}\right)^{\frac{1}{\alpha}} H_y. \tag{31}$$

Equation (31) holds the key for endogenous determination of technology biases. This equation summarizes the incentives to innovate different types of technologies. To see this, we rewrite (31) as $(p_l)^{\frac{1}{\alpha}} L = (p_h^x)^{\frac{1}{\alpha}} H_x = (p_h^y)^{\frac{1}{\alpha}} H_y$, where p_l, p_h^x, and p_h^y are prices of the three types of intermediate goods.[14] It can be verified that the profit from innovating labor-complementary machine

[12] Note that $\pi_l(j) = \xi_l(j)M_l(j) - q_l(j)M_l(j) = \frac{\alpha}{1-\alpha} q_l(j)M_l(j)$.

[13] The growth rate of the economy can be shown to exhibit a scale effect (i.e., it rises with total labor force) that is inconsistent with time series data (Jones, 1995). As noted by Acemoglu (1998), this scale effect is not important for the study of endogenous technology bias and can be removed by imposing the restriction $\gamma_l + \gamma_x + \gamma_y = \bar{\gamma}$.

[14] This equation is derived from profit maximization of intermediate-good firms, which implies that $p_l = w_l/(\alpha A)$, $p_h^x = w_h/(\alpha B_x)$, and $p_h^y = w_h/(\alpha B_y)$.

j equals $\pi_l(j) = \alpha(1-\alpha)^{\frac{1-\alpha}{\alpha}} q_l(j)(p_l)^{\frac{1}{\alpha}} L$, and the profit from innovating skill-complementary machine j in sector s equals $\pi_s(j) = \alpha(1-\alpha)^{\frac{1-\alpha}{\alpha}} q_s(j)(p_h^s)^{\frac{1}{\alpha}} H_s$. Thus, $(p_l)^{\frac{1}{\alpha}} L$ measures the incentive to innovate labor-complementary technologies, $(p_h^x)^{\frac{1}{\alpha}} H_x$ measures the incentive to innovate skill-complementary technologies for sector X, and $(p_h^y)^{\frac{1}{\alpha}} H_y$ measures the incentive to innovate skill-complementary technologies for sector Y. In other words, there are two determinants of the incentive for innovating a particular type of technology: (1) the price of the intermediate good that uses the technology, and (2) the number of workers who use the technology. Acemoglu (1998) terms the first "price effect" and the second "market size effect".

Define $\beta \equiv (\beta_x^{\frac{1}{\alpha}} + \beta_y^{\frac{1}{\alpha}})^{\alpha}$ as the overall skill bias of technologies in the economy, and $\theta \equiv \beta_x/\beta_y$ as the sector bias of technologies. Equation (31) establishes

$$\beta = \omega h^{\alpha}, \tag{32}$$

$$\theta = (H_x/H_y)^{\alpha}. \tag{33}$$

Equation (32) shows that the skill bias of technologies in a country depends on its skill abundance and relative wages. The dependence of β on skill abundance reflects a market size effect: the more skilled workers, the larger the market for skill-complementary technologies, and the higher the skill bias of technologies. The dependence of β on relative wages reflects a price effect: the higher the relative wage of skilled workers, the higher the relative price of skill-intensive intermediate goods, and the higher the incentive for innovating skill-complementary technologies.[15] Equation (33) shows that the sector bias of technologies depends on the relative employment of skilled workers in the two sectors.[16] This equation reflects a market size effect: a higher ratio of H_x/H_y implies a higher relative demand for machines used by skilled workers in sector X,

[15]Note that the relationship between ω and β in our model is the opposite of what is assumed in the induced innovation literature of the 1960s. In our model, an increase in the relative price of a factor stimulates technical progress that augments the factor. By contrast, in the induced innovation literature, an increase in the relative price of a factor induces technical progress that saves the factor.

[16]It is worth noting that in our model, sector bias of technologies is driven by sectoral differences in skill-augmenting technologies. This explains why θ depends on H_x/H_y. In general, sector bias can be driven by sectoral differences in both skill-augmenting and labor-augmenting technologies. This general case is more complicated and we do not pursue it in this paper.

which stimulates innovation of skill-complementary machines designed for sector X, causing θ to rise. Since sector bias is specified for technologies that augment the same factor, relative wages do not play a role in the determination of θ.

The index β measures the overall skill bias of technologies in the economy. To see skill bias of technologies in each sector, we obtain from the definitions of β and θ:

$$\beta_x = \frac{\theta\beta}{(\theta^{\frac{1}{\alpha}} + 1)^{\alpha}}, \qquad \beta_y = \frac{\beta}{(\theta^{\frac{1}{\alpha}} + 1)^{\alpha}}. \tag{34}$$

These two equations link sectoral skill biases β_x and β_y with the overall skill-bias index β and the sector-bias index θ.

3 General Equilibrium under Autarky

In this section we solve a general equilibrium for a closed economy. We first characterize the supply side of the economy treating p as fixed, and then introduce the demand side to determine p. This procedure allows us to investigate the Stolper-Samuelson and Rybczynski relationships in this model, which are central to trade analysis in the next section.

Suppose p is fixed. Firms incur a unit cost of c_x to produce good X, and a unit cost of c_y to produce good Y. Perfect competition equates unit cost to price. *If both goods are produced,* then zero-profit conditions are met in both sectors. From section 2.1 we know that the two zero-profit conditions imply equation (9). Using (5), (6), and (34) we rewrite equation (9) as

$$\omega = \left(\frac{p^{\sigma-1}\theta^{\sigma-1} - 1}{1 - p^{\sigma-1}} \right)^{\frac{1}{\sigma-1}} \frac{\beta}{(\theta^{\frac{1}{\alpha}} + 1)^{\alpha}}. \tag{35}$$

When technology is exogenous, equation (35) determines ω as a positive function of p, which is known as the Stolper-Samuelson theorem. Equation (35) shows that ω also depends on factor bias β and sector bias θ of technologies. If skill-biased technical progress occurs in both sectors at the same rate (i.e., β increases and θ remains constant) or is faster in the skill-intensive sector (i.e., both θ and β increase), then ω rises.

As we have shown in section 2.2, the overall factor bias of technologies in the economy is determined in the steady state according to

$$\beta = \omega h^{\alpha}. \tag{36}$$

Substituting (36) into (35) we find that ω cancels out! The reason is that an increase in β would cause a proportionate increase in ω to satisfy zero-profit conditions (at fixed p and θ), and an increase in ω would cause a proportionate increase in β to satisfy the factor-bias equation. This feature of the model implies a relationship between θ and p, which we obtain from substituting (36) into (35) and rearranging:

$$\left(\frac{(\theta^{\frac{1}{\alpha}} + 1)^{\alpha(\sigma-1)} + h^{\alpha(\sigma-1)}}{(\theta^{\frac{1}{\alpha}} + 1)^{\alpha(\sigma-1)} + \theta^{\sigma-1} h^{\alpha(\sigma-1)}} \right)^{\frac{1}{\sigma-1}} = p. \tag{37}$$

The left-hand side of (37) decreases in θ and h. This establishes

Lemma 1 (Sector bias-price relationship). *$d\theta/dp < 0$.*

Lemma 1 says that an increase in the relative price of the skill-intensive good must be balanced by technical progress *biased toward the labor-intensive sector.* That is, technical progress must be faster in the labor-intensive sector than in the skill-intensive sector.[17] The intuition is as follows. Imagine an exogenous increase in p. A higher p implies a higher p_h^x/p_h^y, which in turn implies a higher relative price of skill-complementary machines for sector X. This induces innovations directed toward skill-complementary technologies for sector X. As the relative productivity of skilled workers in sector X increases because of the use of higher quality machines, p_h^x/p_h^y decreases, inducing innovations directed toward skill-complementary technologies for sector Y. In equilibrium, technical progress in sector Y must be faster than that in sector X to maintain zero-profit conditions in both sectors. If an increase in p were accompanied by technical progress

[17] Since A is the same for both sectors, a sector bias toward Y means that B_y increases faster than B_x. This sector bias refers to skill-biased (labor-biased) technical progress if both B_x and B_y grow faster (slower) than A. It is also possible that technical progress is skill-biased in one sector and labor-biased in the other.

biased toward the skill-intensive sector, then all firms would find it more profitable to produce the skill-intensive good, which would lead to a complete specialization situation.

Next we derive the effect of p on ω. This effect works through both the factor markets and the technology markets. As shown in section 2.1, factor-market equilibrium implies

$$\left(\frac{X}{Y}\right)^s = \left(\frac{h - h_y}{h_x - h}\right)\left(\frac{1+\omega h_y}{1+\omega h_x}\right)^{\frac{\sigma}{1-\sigma}}. \tag{38}$$

Turning to the technology market, we know from section 2.2 that the sector bias $\theta = (H_x/H_y)^\alpha$. This establishes the equality on the left-hand side of the following equation:

$$\theta^{\frac{1}{\alpha}} = \frac{H_x}{H_y} = \left(\frac{1+\omega h_x}{1+\omega h_y}\right)^{\frac{\sigma}{1-\sigma}}\left(\frac{h_x}{h_y}\right)\left(\frac{X}{Y}\right)^s. \tag{39}$$

The equality on the right-hand side of equation (39) shows relative skill employment as a product of relative unit skill requirement and relative output, where unit skill requirements are obtained from partial differentiation of unit cost functions with respect to the wage of skilled labor. Substituting (38) into (39), using $h_x/h_y = \theta^{\sigma-1}$ from (5) and (6), and rearranging, we can state the full-employment condition as

$$\frac{\theta^{\frac{1}{\alpha}-\sigma+1}}{1+\theta^{\frac{1}{\alpha}-\sigma+1}}h_x(\omega,\theta) + \frac{1}{1+\theta^{\frac{1}{\alpha}-\sigma+1}}h_y(\omega,\theta) = h, \tag{40}$$

where $h_x(\omega,\theta)$ and $h_y(\omega,\theta)$ can be obtained from substituting (32) and (34) into (5) and (6):

$$h_x(\omega,\theta) = \frac{\theta^{\sigma-1}h^{\alpha(\sigma-1)}}{\omega(\theta^{\frac{1}{\alpha}}+1)^{\alpha(\sigma-1)}}, \tag{41}$$

$$h_y(\omega,\theta) = \frac{h^{\alpha(\sigma-1)}}{\omega(\theta^{\frac{1}{\alpha}}+1)^{\alpha(\sigma-1)}}. \tag{42}$$

Substituting (41) and (42) into (40) we can express ω as a function of θ,

$$\omega = \frac{h^{\alpha(\sigma-1-\frac{1}{\alpha})}}{(\theta^{\frac{1}{\alpha}-\sigma+1}+1)(\theta^{\frac{1}{\alpha}}+1)^{\alpha(\sigma-1-\frac{1}{\alpha})}}. \tag{43}$$

Differentiating ω with respect to θ, we find that $d\omega/d\theta < 0$ if $\sigma > (1+1/\alpha)$ and $d\omega/d\theta > 0$ if $\sigma < (1+1/\alpha)$. Applying Lemma 1, we establish

Lemma 2 (Wage-price relationship). $d\omega/dp > 0$ if and only if $\sigma > (1+1/\alpha)$.

Lemma 2 says that an increase in the relative price of the skill-intensive good will raise the wage of skilled workers as long as factor substitution is sufficiently elastic. To understand the condition $\sigma > (1+1/\alpha)$, we examine the full-employment equation (40). This equation implies that the allocation of unskilled labor between sectors, L_x/L_y, is determined by $\theta^{\frac{1}{\alpha}-\sigma+1}$. Two effects are involved here. First, $h_x/h_y = \theta^{\sigma-1}$. That is, a one percent increase in θ will lead to $(\sigma-1)$ percent increase in h_x/h_y; we call it a "factor intensity effect". Second, $H_x/H_y = \theta^{\frac{1}{\alpha}}$. That is, a one percent increase in θ corresponds to $(1/\alpha)$ percent increase in H_x/H_y; we call it a "technology market effect". If $\sigma > (1+1/\alpha)$, then the factor intensity effect dominates the technology market effect. In this case, a decrease in θ (induced by an increase in p) will increase the unskilled labor allocated to the skill-intensive sector. To maintain full employment, the skill intensity of the skill-intensive sector must fall and hence ω must rise.

Having derived the effect of p on ω, we immediately obtain the effect of p on the factor bias index β. Substituting (43) into (36) we obtain

$$\beta = \frac{h^{\alpha\sigma-1}}{(\theta^{\frac{1}{\alpha}-\sigma+1}+1)(\theta^{\frac{1}{\alpha}}+1)^{\alpha(\sigma-1-\frac{1}{\alpha})}}. \tag{44}$$

Equation (44) establishes

Lemma 3 (Factor bias-price relationship). $d\beta/dp > 0$ if and only if $\sigma > (1+1/\alpha)$.

Lemma 3 says that an increase in the relative price of the skill-intensive good will induce skill-biased technical progress, provided that factor substitution is sufficiently elastic.

Next we turn to an important relationship in trade theory, namely the Rybczynski relationship, which describes the response of relative output to changes in factor abundance at fixed commodity prices. If technology is exogenous, an increase in h induces skill-intensity adjustments and resource reallocation, causing relative supply $(X/Y)^s$ to increase at constant p. This result is known as the Rybczynski theorem. In our model, an increase in h induces not only the usual skill-intensity adjustments at constant technology, but also changes in technologies. To see whether the Rybczynski theorem still holds, we obtain an expression for $(X/Y)^s$ by substituting $p = [(1+\omega h_x)/(1+\omega h_y)]^{\frac{1}{1-\sigma}}$ from zero-profit conditions into (39),

$$\left(\frac{X}{Y}\right)^s = \theta^{\frac{1}{\alpha}-\sigma+1} p^{-\sigma}. \tag{45}$$

Partially differentiate $(X/Y)^s$ with respect to h we obtain

$$\frac{\partial (X/Y)^s}{\partial h} = \frac{\partial (X/Y)^s}{\partial \theta}\frac{\partial \theta}{\partial h}. \tag{46}$$

From equation (37) we know that θ decreases in h at fixed p. From equation (45) we find that $(X/Y)^s$ decreases in θ at fixed p if and only if $\sigma > (1+1/\alpha)$. Therefore, $\partial(X/Y)^s/\partial h > 0$ if and only if $\sigma > (1+1/\alpha)$. This establishes

Lemma 4 (Output-endowment relationship). $(X/Y)^s$ increases in h at constant p if and only if $\sigma > (1+1/\alpha)$.

Finally, we determine p in the commodity market equilibrium. We first examine the response of relative supply $(X/Y)^s$ to p. Substituting $p = [(1+\omega h_x)/(1+\omega h_y)]^{\frac{1}{1-\sigma}}$ from zero-profit conditions into (38) yields an expression for $(X/Y)^s$:

$$\left(\frac{X}{Y}\right)^s = \left(\frac{h-h_y}{h_x-h}\right) p^{-\sigma}. \tag{47}$$

We can decompose the effect of p on $(X/Y)^s$ into an effect at constant technology and an effect due to endogenous technical change. Comparing (45) and (47) we find that the second effect works through θ. Differentiating (47) with respect to p yields

$$\frac{d(X/Y)^s}{dp} = \frac{\partial(X/Y)^s}{\partial p} + \frac{\partial(X/Y)^s}{\partial\theta}\frac{d\theta}{dp}. \tag{48}$$

At constant technology, an increase in p raises ω and hence lowers both h_x and h_y; to maintain full employment, sector X must expand and sector Y shrink; this shows $\partial(X/Y)^s/\partial p > 0$. From equation (45) we find that $\partial(X/Y)^s/\partial\theta < 0$ if and only if $\sigma > (1 + 1/\alpha)$; according to Lemma 1, $d\theta/dp < 0$. These results establish

Lemma 5 (Output-price response). $d(X/Y)^s/dp > 0$ if and only if $\sigma > (1 + 1/\alpha)$.

Lemma 5 states the condition for a positive output-price response. In Figure 1, we draw relative supply as a positively sloped RS curve. With Cobb-Douglas preferences, the relative demand for good X is given by

$$\left(\frac{X}{Y}\right)^d = \frac{\lambda}{(1-\lambda)p}. \tag{49}$$

Equation (49) defines a negatively sloped relative demand curve, which we draw in Figure 1 as the RD curve. The intersection of RS and RD gives the equilibrium value of p.

4 Effects of International Trade

In this section we investigate the effects of international trade in a two-country world economy. Our analysis is an extension of the "countries A and B" version of the HO model, with the two countries differing only in factor abundance. We first consider trade in final goods, then trade in intermediate goods, and finally trade in technologies. Throughout this section we assume that both countries innovate and there is no international technology diffusion of the public-good nature. In the next section we will examine a "North-South" version of the model in which new technologies are innovated in the North and diffused to the South.

4.1 International Trade in Final Goods

Consider two countries, Home and Foreign, that differ in skill abundance. Let Home be the skill-abundant country and Foreign be the labor-abundant country. The autarky equilibrium in each country is as described in the previous section. Now we introduce free trade in final goods and examine the effects of trade opening in each country.

Trade patterns

The first issue is trade patterns. In the 2x2 HO model with constant technology, the skill (labor)-abundant country has a comparative advantage in the skill (labor)-intensive good and exports the skill (labor)-intensive good in a free trade equilibrium. This result is known as the Heckscher-Ohlin theorem. In our model with endogenous technology, countries derive comparative advantage not only from differences in factor abundance, but also from differences in technology, which are endogenously determined by differences in factor abundance. To see the effects of trade opening, we need to first know whether the HO theorem still holds.

Figure 1 provides the answer. According to Lemma 4, a decrease in h implies a decrease in $(X/Y)^s$ at any given p, shifting ES to the left. Thus, the ES curve depicts the excess relative supply of the skill-abundant country (Home), and the E^*S^* curve depicts the excess relative supply of the labor-abundant country (Foreign). The autarky equilibrium of Home and Foreign is located at points E and E^*, respectively. The autarky relative prices indicate that Home has a comparative advantage in the skill-intensive good and Foreign has a comparative advantage in the labor-intensive good. Point E^w depicts the free trade equilibrium where world relative demand equals world relative supply. At the free-trade equilibrium world price p^w, Home exports the skill-intensive good and imports the labor-intensive good, while Foreign exports the labor-intensive good and imports the skill-intensive good. We summarize this result in:

Proposition 1. Consider two countries whose economies are as described in sections 2 and 3 and who differ only in skill abundance. If they open to free trade in final goods, the skill (labor)-abundant country will export the skill (labor)-intensive good and import the labor (skill)-intensive good, provided that factor substitution is sufficiently elastic ($\sigma > 1 + 1/\alpha$).

Proposition 1 identifies the conditions for the HO theorem to hold in the presence of endogenous technology. These conditions guarantee that the comparative advantage derived directly from differences in factor abundance is not reversed by the comparative advantage derived from differences in technology, which are induced by differences in factor abundance. It should be noted that Proposition 1 is derived under the assumption of diversified production, i.e., both goods are produced in each country in the free trade equilibrium. In the HO model, diversified production requires that the two countries have similar factor abundance. In our model, since the two countries differ in both factor abundance and technology, diversified production requires that the two countries have similar technology-adjusted factor abundance.

Technology Biases

Trade opening affects technology biases through p. Since p moves in opposite directions in the two countries after trade opening, the implications for technology biases are opposite in the two countries. We will proceed the analysis assuming that the conditions for Proposition 1 hold. In particular, we assume that $\sigma > (1 + 1/\alpha)$.

The effects of trade opening on sector bias and factor bias can be derived from Lemma 1 and Lemma 3, respectively. In the skill-abundant country, trade opening increases p, which induces technical progress biased toward the labor-intensive sector to maintain diversified production in equilibrium (Lemma 1). An increase in p also stimulates innovations directed toward skill-complementary technologies, causing β to rise (Lemma 3). The converse is true in the labor-abundant country.

It should be pointed out that β is a measure of overall skill bias in an economy. Sectoral skill biases (β_x and β_y) depend on both β and θ. When trade opening causes β to increase and θ to decrease in the skill-abundant country, for example, β_y will rise but β_x may rise or fall. We can show that the condition for β_x to rise with p is that skill intensities of the two sectors are sufficiently different, $\theta > \hat{\theta}$.[18] For example, if $\sigma = 3$ and $\alpha = 2/3$, then $\hat{\theta} = 2.5$. If this condition holds, trade opening will give rise to skill (labor)-biased technical progress in both sectors in the skill (labor)-abundant country.

We summarize these results in:

Proposition 2. Consider two countries whose economies are as described in sections 2 and 3 and who differ only in skill abundance. If factor substitution is sufficiently elastic ($\sigma > 1 + 1/\alpha$), opening trade in final goods will cause skill (labor)-biased technical progress in the skill (labor)-abundant country. Moreover, technical progress will be biased toward the labor (skill)-intensive sector in the skill (labor)-abundant country.

Proposition 2 reflects the responses of innovators to changes in relative market size and relative prices. When countries innovate for their own domestic markets, trade opening does not cause any market size effect that would shape the overall skill bias of an economy. However, trade opening raises the price of the skill-intensive final good in Home, which implies higher prices for skill-intensive intermediate goods and hence a higher incentive for innovating skill-complementary technologies; the converse is true in Foreign. Because of these price effects, Home will use more skill-biased technologies after opening to trade, and Foreign will use more labor-biased technologies. Although trade opening does not change the market size of skill-complementary technologies relative to that of labor-complementary technologies, it will affect the relative market size of skill-complementary technologies used in different sectors. As a result, the sector bias of technical progress will change in both countries after trade opening.

[18] Substituting (44) into the expression for β_x in (34), we obtain β_x as a function of θ. Differentiating β_x with respect to θ we find that $d\beta_x/d\theta < 0$ if and only if $(1+\theta^{\sigma-\frac{1}{\alpha}-1})/(\theta^{\sigma-1}-1) < \sigma - 1/\alpha - 1$. This inequality implies a critical value $\hat{\theta}$.

It is worth pointing out that the trade effects on technology biases would remain the same for the skill-abundant country if it opens trade to a labor-abundant country which does not do R&D, as long as this trade opening increases p. In this North-South context, the results in Proposition 2 may be linked to a hypothesis of Wood (1994). Wood observes that "a common reaction of Northern firms to Southern competition has been to seek new ways of producing with less unskilled labor" (p. 10), and he argues that trade with the South may induce "defensive labor-saving innovation" (p. 159). We find in Proposition 2 that opening trade to the labor-abundant country will induce skill-biased technical progress in the skill-abundant country to save unskilled labor. Moreover, we find that opening trade to the labor-abundant country will induce faster technical progress in the labor-intensive sector of the skill-abundant country to "defend" its labor-intensive sector. If the labor-abundant country also innovates, such "defensive" technical progress would also occur there in the form of labor-biased technical progress and faster technical progress in the skill-intensive sector.

Relative Wages

We now turn to the effect of trade opening on relative wages. In the standard HO model, trade opening affects relative wages through the Stolper-Samuelson channel. In the present model, trade opening affects relative wages not only through the Stolper-Samuelson channel, but also through endogenous technical progress.

As Figure 1 shows, trade opening causes p to rise in the skill-abundant country and fall in the labor-abundant country. To see how a change in p affects relative wages, we observe the factor-bias equation $\beta = \omega h^{\alpha}$ which implies that ω changes in the same direction as β. Since we have already shown how p affects β, the effect of p on ω follows immediately. This leads to:

Proposition 3. Consider two countries whose economies are as described in sections 2 and 3 and who differ only in skill abundance. If factor substitution is sufficiently elastic ($\sigma > 1 + 1/\alpha$), then opening trade in final goods will increase (decrease) the relative wage of skilled workers in the skill (labor)-abundant country.

Proposition 3 states that international trade will cause relative wages to move in the same direction as predicted by the Stolper-Samuelson theorem, despite that we consider both the Stolper-Samuelson effect and the trade-induced endogenous technical progress effect. To understand why, recall equation (35) which shows that ω depends on relative commodity price p, sector bias θ, and factor bias β. Notice that ω and β are linearly related in the zero-profit equation (35) and also in the factor-bias equation (36). These two linear relationships imply, as equation (37) shows, that the wage effect of p and the wage effect of θ exactly offset each other such that ω is determined solely by the effect of β. Under the assumptions on factor substitution elasticity and price-output response stated in Proposition 2, trade opening will induce skill (labor)-biased technical progress in the skill (labor)-abundant country. It follows that wage inequality will rise (fall) in the skill (labor)-abundant country after trade opening. We should emphasize that although the direction of the trade effect on relative wages in our model is the same as that in the HO model, it has incorporated both the Stolper-Samuelson effect and the trade-induced technology effects.

4.2 International Trade in Intermediate Goods

We now consider trade in intermediate goods. In section 2.2 we showed that prices of intermediate goods are given by $p_l = w_l/(\alpha A)$, $p_h^x = w_h/(\alpha B_x)$, and $p_h^y = w_h/(\alpha B_y)$; hence $\theta = p_h^y/p_h^x$ measures the price of good Z_y relative to that of good Z_x.

Suppose countries are already open to free trade in final goods. Is there still an incentive for trade in intermediate goods? Equation (37) provides the answer. This equation shows that θ decreases in h at any given p. Thus, free trade in final goods does not equalize prices of intermediate goods between countries, and the skill-abundant country will have a lower $\theta = p_h^y/p_h^x$ than the labor-abundant country. Because this relative price is fixed by skill abundance, opening trade in intermediate goods will lead to complete specialization. The skill-abundant country (Home) will produce only good Z_y, while the labor-abundant country (Foreign) will produce only good Z_x. Since technologies (machines) are purchased only by domestic firms, R&D

will be directed towards M_y in Home and M_x in Foreign. Using an asterisk to denote variables of Foreign, we have $(p_l)^{\frac{1}{\alpha}}L = (p_h^y)^{\frac{1}{\alpha}}H$ in Home and $(p_l)^{\frac{1}{\alpha}}L^* = (p_h^x)^{\frac{1}{\alpha}}H^*$ in Foreign in the steady state equilibrium. Using $p_l = w_l/(\alpha A) = w_l^*/(\alpha A^*)$, $p_h^x = w_h^*/(\alpha B_x^*)$, and $p_h^y = w_h/(\alpha B_y)$, we obtain $\beta_y = \omega p_l/p_h^y = \omega h^\alpha$ and $\beta_x = \omega^* p_l/p_h^x = \omega^* h^{*\alpha}$. These steady-state technology market conditions imply that $\theta = p_h^y/p_h^x = (h^*/h)^\alpha$. By definition, $\theta = \beta_x/\beta_y = (\omega^*/\omega)(h^*/h)^\alpha$. Therefore, $\omega = \omega^*$. That is, free trade in intermediate goods equalize relative wages in the two countries. Since skill intensities are functions of relative wages and skill biases, trade in intermediate goods also equalizes h_x and h_y. In addition, while the two countries specialize in goods Z_y and Z_x, they both produce good Z_l. Trade in good Z_l equalizes $p_l = p_l^*$, which implies $w_l/A = w_l^*/A^*$. Thus, trade in intermediate goods equalizes productivity-adjusted wages.

It is useful to observe that trade in intermediate goods results in fixed relative commodity prices of both intermediate goods and final goods. The price of good Z_l relative to the price of good Z_y is fixed at $p_l/p_h^y = h^\alpha$, while the price of good Z_l relative to the price of good Z_x is fixed at $p_l/p_h^x = h^{*\alpha}$. It follows the relative price of the two final goods is fixed at $p = [(1+h^{*\alpha(\sigma-1)})(1+h^{\alpha(\sigma-1)})]^{\frac{1}{1-\sigma}}$.[19] As noted above, the two countries have the same relative wage $\omega = \omega^* = \omega^w$ under free trade. The value of ω^w is determined in the world commodity market equilibrium,[20] which may be higher or lower than the pre-trade value of relative wages in each country.

We summarize the above results in:

Proposition 4. Consider two countries whose economies are as described in sections 2 and 3 and who differ only in skill abundance. If they open to free trade in both final goods and intermediate goods,

(i) the skill (labor)-abundant country will produce and export the skill-intensive intermediate

[19] If intermediate goods are traded and final goods are not, then domestic factor markets will not clear in both countries.

[20] The value of ω^w is a function of factor endowments and technology stocks of both countries. If $A = A^*$, we can show that $\omega^w = (\delta h^{\alpha(\sigma-1)} + h^{*\alpha(\sigma-1)})/(\delta h^w + h^w)$, where $\delta \equiv \lambda(1 + h^{*\alpha(\sigma-1)})/[(1-\lambda)(1+h^{\alpha(\sigma-1)})]$.

good used in the labor (skill)-intensive sector, and both countries will produce and trade the labor-intensive intermediate good;

(ii) relative prices of intermediate goods and final goods will be fixed by the values of factor abundance of the two countries;

(iii) relative wages will be equalized by trade, whose value may be higher or lower than their pre-trade values in each of the two countries.

4.3 International Trade in Technologies

We now consider trade in technologies. Suppose firms can purchase blueprints of machines from foreign innovators. We assume that intellectual property rights are fully protected both domestically and abroad so that an innovator will receive full compensation whether she sells her invention to a domestic firm or a foreign firm.

Given free trade in technologies, countries will use identical technologies. If final goods are also freely traded and if the two countries have similar factor abundance, factor prices will be equalized across countries as in the HO model. The equalization of factor prices implies that the world trading equilibrium is an integrated equilibrium.[21] The integrated world economy operates in the same way as the autarky economy of Home or Foreign, with skill abundance equal to $h^w \equiv (H + H^*)/(L + L^*)$. Thus, a move from autarky to free trade (in final goods and technologies) means a decrease in h for Home and an increase in h^* for Foreign. This allows us to derive the effects of trade opening from the effects of a change in h in a closed economy.

To see the effect of skill supply h on sector bias θ, we equate $(X/Y)^s$ in (45) and $(X/Y)^d$ in (49) to obtain

$$\theta(h) = \left(\frac{\lambda p(h)^{\sigma - 1}}{1 - \lambda} \right)^{\frac{1}{\frac{1}{\alpha} - \sigma + 1}}. \tag{50}$$

[21] There is no incentive for trade in intermediate goods because their prices are equalized by trade in final goods *and* technologies.

In the end of the previous section we pointed out that $dp/dh < 0$ as long as $\sigma > (1 + 1/\alpha)$ and excess supply responds positively to price. Observing equation (50) we find that $d\theta/dp < 0$ if $\sigma > (1 + 1/\alpha)$. Therefore, we have

Lemma 7 (Sector bias-endowment relationship). $d\theta/dh > 0$ if $\sigma > (1 + 1/\alpha)$ and the response of excess supply to price is positive.

Intuitively, Lemma 7 says that an increase in skill supply results in more production of the skill-intensive good, causing its price to fall. The decrease in the price of the skill-intensive good is balanced by faster technical progress in the skill-intensive sector in the steady state.

To see the effect of skill supply h on factor bias β, we substitute (50) into (44) to obtain

$$\beta(h) = \frac{h^{\alpha(\sigma - \frac{1}{\alpha})}}{\Theta(h)}, \tag{51}$$

where $\Theta(h) \equiv (\theta(h)^{\frac{1}{\alpha} - \sigma + 1} + 1)(\theta(h)^{\frac{1}{\alpha}} + 1)^{\alpha(\sigma - 1 - \frac{1}{\alpha})}$. This equation shows that h affects β directly and indirectly through θ. The direct effect is positive if $\sigma > 1/\alpha$. The indirect effect is negative if $\sigma > (1 + 1/\alpha)$ and the response of excess supply to price is positive. The condition for an increase in skill supply to induce an increase in β is that the direct effect dominates the indirect effect through sector bias. If we define $\varepsilon_\theta \equiv \Theta'(h)h/\Theta(h)$, which measures the size of the indirect sector-bias effect, we can establish

Lemma 8 (Factor bias-endowment relationship). $d\beta/dh > 0$ if $\sigma > (1+1/\alpha)$, the response of excess supply to price is positive, and $\varepsilon_\theta < \alpha\sigma - 1$.

Next we derive the effect of skill supply h on wage inequality ω. Substituting (50) into (43) we obtain

$$\omega(h) = \frac{h^{\alpha(\sigma - 1 - \frac{1}{\alpha})}}{\Theta(h)}. \tag{52}$$

Equation (52) contains three effects. First, at fixed technology, an increase in h results in the substitution of skilled labor for unskilled labor, which lowers ω. Second, at fixed sector bias, an increase in h induces skill-biased technical progress, which raises ω. Third, when $\sigma > (1 + 1/\alpha)$ and the response of excess supply to price is positive, an increase in h has a negative effect on ω through the sector-bias term Θ. The condition for an increase in skill supply to raise wage inequality is that the factor-bias effect dominates the sum of the factor substitution effect and the sector-bias effect. We can establish

Lemma 9 (Wage-endowment relationship). $d\omega/dh > 0$ if $\sigma > (1 + 1/\alpha)$, the response of excess supply to price is positive, and $\varepsilon_\theta < \alpha\sigma - \alpha - 1$.

Lemma 9 identifies the conditions for wage inequality to respond positively to skill supply. This is a central result of Acemoglu (1998) and Kiley (1999), who argue that the increase in skill supply in the United States in the 1970s is the main reason for rising wage inequality in the 1980s. Lemma 9 generalizes this result and shows that the conditions for it to hold are more stringent than those identified in the existing literature.

Lemmas 7-9 help to establish:

Proposition 5. Consider two countries whose economies are as described in sections 2 and 3 and who differ only in skill abundance. If factor substitution is sufficiently elastic ($\sigma > 1 + 1/\alpha$), response of excess supply to price is positive, and intellectual property rights are fully protected internationally, opening to free trade in final goods and technologies has the following implications:

(i) The skill (labor)-abundant country will experience technical progress biased toward the labor (skill)-intensive sector;

(ii) The trade-induced technical progress will be labor (skill)-biased in the skill (labor)-abundant country if $\varepsilon_\theta < \alpha\sigma - 1$;

(iii) Wage inequality will fall (rise) in the skill (labor)-abundant country if $\varepsilon_\theta < \alpha\sigma - \alpha - 1$.

Comparing Proposition 5 and Proposition 3, we find that the wage effects of international trade in final goods are reversed by the wage effects of international trade in technologies under the specified assumptions.[22] The reason is that when technologies are traded internationally, incentives to innovate are determined by the size of the world market. After trade opening, innovators in the skill-abundant country see an increase in the market size of labor-complementary machines relative to the market size of skill-complementary machines, which induces innovations directed toward labor-complementary machines in order to meet the demand from the labor-abundant country. In the meantime, trade opening increases the price of the skill-intensive good in the skill-abundant country, which induces innovations directed toward skill-complementary machines. Under the specified assumptions, the market size effect dominates the price effect; hence trade opening leads to a decrease in wage inequality in the skill-abundant country. The converse is true in the labor-abundant country.

5 International Technology Diffusion

The previous section showed the effects of international trade in two countries that differ only in factor abundance. To address North-South issues, we modify the model in this section by introducing asymmetries in technology acquisition and protection. Labeling the skill-abundant country as North and the labor-abundant country as South, we assume that new technologies are invented in the North and are immediately imitated by the South. The South provides no protection of intellectual property rights of foreign technologies; hence Northern innovators receive no compensation from the South. We assume that the marginal cost for Southern firms to imitate a Northern technology equals $q_s(j)/(1-\alpha)$ for machine j of type s. As a result, firms in both the North and the South use the same technology. Although these assumptions are extreme, they help to simplify the analysis and sharpen the results.

[22] Trade in machines would have the same effects as trade in technologies as long as final goods are traded.

5.1 Effects of International Trade

Suppose international technology diffusion occurs irrespective of trade opening. The South takes as given technologies invented in the North; hence its economy functions as in the standard HO model. The North innovates and its economy is as described in section 2. As we learned from section 3, the endogeneity of technologies affects the response of relative supply to relative prices, making it possible that the skill-abundant country has a comparative advantage in the labor-intensive good. We exclude this possibility in the following analysis and assume that the North has a comparative advantage in the skill-intensive good. Thus, opening trade in final goods will cause p to rise in the North and p^* to fall in the South.[23]

What are the effects of trade opening on technology biases and wage inequality in the North? Lemmas 1-3 provide the answer. The increase in p will induce technical progress biased toward the labor-intensive sector (i.e., a decrease in θ). If $\sigma > (1 + 1/\alpha)$, technical progress will be skill-biased (i.e., an increase in β) and Northern wage inequality will rise.

What are the effects of trade opening in the South? Given that the South imitates technologies of the North, technical progress in the South will be the same as technical progress in the North. Since trade opening increases β and decreases θ, the South will experience skill-biased technical progress biased toward the labor-intensive sector. Turning to wage inequality in the South, we find that it is impacted by three effects. First, trade opening lowers the relative price of the skill-intensive good in the South, which pushes down ω^* through the Stolper-Samuelson mechanism. Second, trade opening induces skill-biased technical progress, which pushes up ω^*. Third, trade opening induces a sector bias of technical progress toward the labor-intensive sector, which pushes down ω^*. The relative magnitude of these three effects determines how wage inequality changes in the South after opening to trade.

We summarize the above results in:

[23] International trade in final goods equalizes the prices of intermediate goods in the presence of international technology diffusion.

Proposition 6. Consider a North-South world economy in which the North innovates (as described in section 2) and the South imitates without compensating Northern innovators. If the North (South) has a comparative advantage in the skill (labor)-intensive good and if factor substitution is sufficiently elastic ($\sigma > 1 + 1/\alpha$) in the North, trade opening in final goods has the following implications:

(i) Both the North and the South will experience skill-biased technical progress with a sector bias toward the labor-intensive sector;

(ii) Wage inequality will rise in the North;

(iii) Wage inequality may rise or fall in the South.

Proposition 6(ii) provides a trade account for rising wage inequality in Northern countries (e.g. the United States). North-South trade increases wage inequality in the North because it induces skill-biased technical progress. This trade account is consistent with the observation that rising wage inequality is accompanied by rising skill intensities in industrialized countries. Proposition 6(iii) provides an account for the observation that wage inequality rose in the majority of developing countries that implemented trade liberalization in the past two decades.[24] North-South trade induces innovations of skill-biased technologies in the North, which are imitated by the South, raising the relative demand for skilled workers there.

A comparison between Propositions 5 and 6 indicates that the trade-wages relationship depends critically on the nature of international technology transfer. If technologies can be traded as private goods, then trade opening would increase the relative market size of labor-complementary technologies, stimulating innovations of such technologies in the skill-abundant country and causing its wage inequality to fall (Proposition 5). In contrast, if technologies

[24] For example, Hanson and Harrison (1999) found that wage inequality began to rise in Mexico in 1985 (after a two-decade trend towards decreasing wage inequality) when the country reduced its trade barriers significantly. Robbins (1996) studied nine developing countries that engaged in trade liberalization between the late 1970s and early 1990s. He found evidence that trade liberalization raised wage inequality in Argentina (1976-82), Chile (1975-93), Colombia (1985-89), Costa Rica (1987-93), Mexico (1987-93), the Philippines (1978-88), Taiwan (1978-90), and Uruguay (1991-95), although he also found a few exceptions, namely Argentina (1989-93) and Malaysia (1973-89).

diffuse across countries as public goods, then trade opening would not change the market size for innovators. The effect of trade opening would be to raise the relative price of the skill-intensive good in the skill-abundant country, causing its wage inequality to rise (Proposition 6). Acemoglu (1998) was the first to identify these two contrasting cases and link them to the degree of international protection of intellectual property rights.

5.2 Effects of Skill Supply

In the previous subsection we provided a trade account for rising wage inequality in the North and the South. In this subsection we examine a skill-supply account proposed by Acemoglu (1998) and Kiley (1999). These authors argue that the rapid increase in the supply of college educated labor in the United States during the 1970s constitutes a main reason for rising wage inequality in the United States during the 1980s.[25] In what follows, we identify conditions for this result to hold in the 2x2 model. Moreover, we discuss the effects of an increase in the skill supply in the North on the wage inequality in the South.

Lemma 8 states the conditions for $d\omega/dh > 0$. An increase in h has three effects on ω. First, at constant technology, an increase in h induces substitution of skilled labor for unskilled labor, causing ω to fall. This is the usual factor substitution effect. Second, an increase in h implies an increase in the relative market size for skill-complementary technologies, which induces skill-biased technical progress under the conditions stated in Lemma 7, causing ω to rise. This is a factor-bias effect emphasized in the recent literature on endogenous skill bias. Third, an increase in h induces technical progress biased toward the skill-intensive sector under the conditions stated in Lemma 6, which leads to an increase in the relative supply of the skill-intensive good, causing the price of the skill-intensive good to fall to clear commodity markets and ω to fall to clear labor markets. This is a sector-bias effect identified in our model. Thus, for an increase in skill supply to raise wage inequality in the North, the factor-bias effect must dominate the sum of the factor substitution effect and the sector-bias effect. It is clear that the

[25]For more discussions on this argument, see Acemoglu (2000).

conditions for $d\omega/dh > 0$ are more stringent in our model than those identified in the existing literature (e.g. Acemoglu, 1998).

Interestingly, our model provides an argument that the increase in skill supply of the United States in the 1970s may be a reason for the increase in wage inequality in some developing countries during the 1980s. If we assume an integrated North-South world economy, then wage inequality in both countries would change in the same direction. More realistically, we assume that the South comprises of small open economies who take p as given. As we know from the zero-profit conditions, when p is fixed, technical progress impacts relative wages solely through its sector bias: wage inequality rises (falls) if technical progress is biased toward the skill (labor)-intensive sector, irrespective of its factor bias. We have shown that an increase in Northern skill supply will induce technical progress biased toward the skill-intensive good. Given that Northern technologies are imitated by the South, an increase in Northern skill supply will induce technical progress in the South to be biased toward the skill-intensive sector, hence raising wage inequality in the South. Of course an increase in Northern skill supply will cause p to fall in the South who takes p as given, which implies a Stolper-Samuelson effect that reduces its wage inequality. How wage inequality changes in the South depends on the relative magnitude of the sector-bias effect and the Stolper-Samuelson effect.

We summarize the above results in:

Proposition 7. Consider a North-South world economy in which the North innovates (as described in section 2) and the South imitates without compensating Northern innovators. Suppose the South comprises of small open economies. If conditions in Lemmas 6-8 hold, an increase in the supply of skilled labor in the North has the following implications:

(i) Both the North and the South will experience skill-biased technical progress with a sector bias toward the skill-intensive sector;

(ii) Wage inequality will rise in the North;

(iii) Wage inequality may rise or fall in the South.

Proposition 7(ii) provides a skill-supply account for rising wage inequality in the North. An increase in skill supply in the North stimulates innovations of skill-complementary technologies, causing wage inequality to rise under the conditions stated in Lemmas 6-8. Proposition 7(iii) provides a skill-supply account for rising wage inequality in the South. An increase in skill supply in the North induces technical progress biased toward the skill-intensive sector. If the South imitates Northern technologies, technical progress biased toward the skill-intensive sector will cause wage inequality to rise in the South. Proposition 7(iii) provides a good example that shows the importance of considering sector bias of technical progress. To explain rising wage inequality in developing countries that are small open economies, what needs to be shown is not that technical progress is biased toward skilled labor, but that technical progress is biased toward the skill-intensive sector. Together Propositions 6 and 7 suggest that the trade account and the skill-supply account may be complementary in explaining rising wage inequality in developed and less developed countries in the past two decades.

6 Conclusions

In this paper we endogenize factor bias and sector bias of technical progress in the 2x2x2 Heckscher-Ohlin framework. Using an approach pioneered by Acemoglu (1998), we determine factor bias of technical progress as a function of factor abundance and relative commodity prices. We extend Acemoglu's (1998) approach to determine sector bias of technical progress as a function of relative factor employment in the two sectors.

We examine how the endogeneity of technology affects some key relationships in the HO model. We find that if factor substitution is sufficiently elastic, then the Rybczynski relationship between relative output and factor abundance remains valid. We find that relative commodity prices impact relative wages in the same direction as predicted by the Stolper-Samuelson theorem, although the channels of this effect are different. We show the conditions under which trade patterns are still predicted by the Heckscher-Ohlin theorem.

We use the model to examine the effects of international trade on technology bias and wage inequality. We find that for two countries who do their own R&D, opening trade in final goods will induce skill-biased technical progress and increase wage inequality in the skill-abundant country, and induce labor-biased technical progress and decrease wage inequality in the labor-abundant country. We show that opening to trade in intermediate goods will in general have an ambiguous effect on wage inequality. We find that if the two countries open to trade in both goods and technologies, wage inequality will fall in the skill-abundant country and rise in the labor-abundant country as long as a sector-bias effect is sufficiently small.

We also consider a North-South world economy where the North innovates and the South imitates. We find that trade opening will induce skill-biased technical progress biased toward the labor-intensive sector in both the North and the South, causing wage inequality to rise in the North and possibly in the South. In this context, we reexamine an argument by Acemoglu (1998) and Kiley (1999) that explains rising wage inequality in the United States during the 1980s as a result of skill-biased technical progress induced by the rapid increase in the supply of college educated labor in the United States during the 1970s. We show that the conditions for it to hold are more stringent in our model than identified by the aforementioned studies. Furthermore, we show that if technological innovations in the United States are the main source for technical progress in small open economies in the South, an increase in U.S. skill supply, by inducing technical progress biased toward the skill-intensive sector, may raise the wage inequality in these countries. Our results suggest that rising North-South trade openness and rising skill supply in the North may be complementary explanations for rising wage inequality in both the North and the South in the past two decades.

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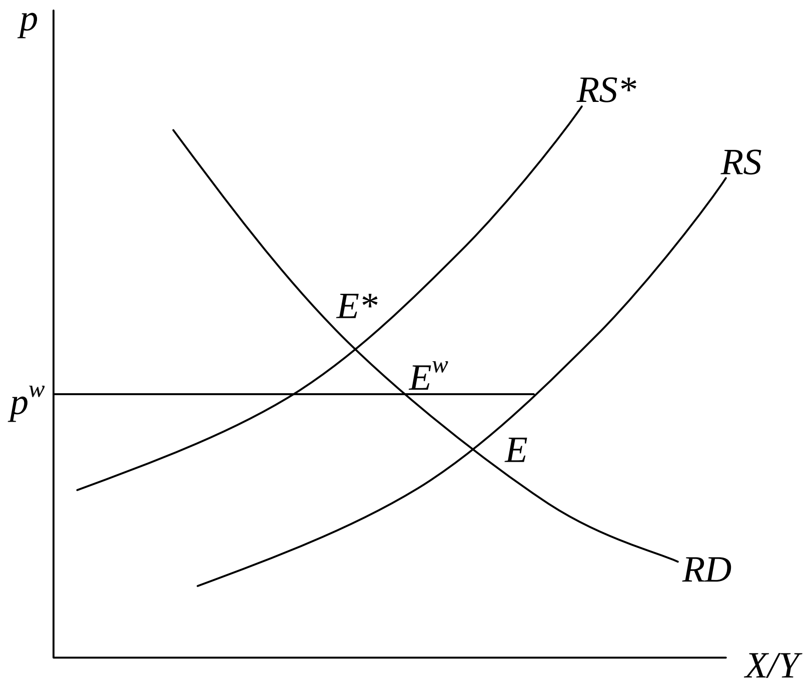

Figure 1