A Schumpeterian Model of Protection and Relative Wages

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This paper presents a dynamic general equilibrium model of R&D-based trade between two structurally identical countries in which both innovation and skill acquisition rates are endogenously determined. Trade liberalization increases R&D investment and the rate of technological change. It also reduces the relative wage of unskilled workers and results in skill upgrading within each industry when R&D is the skilled-labor intensive activity relative to manufacturing of final products. Time-series evidence from the United States and simulation analysis support the empirical relevance of the model, which offers a North–North trade explanation for increasing wage inequality. (*JEL* F10, F12, F13, D32, D41)

> The sources of U.S. difficulties are overwhelmingly domestic, and the nation's plight would be much the same even if world markets had not become more integrated . . . less skilled workers in particular are suffering because a high-technology economy has less and less demand for their services. Our trade with the rest of the world plays at best a small role (Paul R. Krugman and Robert Lawrence, 1994).

The relative demand for less skilled labor has decreased dramatically over time, particularly in the 1980's.[1] In several countries including the United States, the decline in the relative demand for less skilled workers has contributed to a significant increase in wage inequality.[2] In several European countries where labor markets exhibit downward wage rigidities, this decline revealed itself primarily through a sharp rise in unemployment.[3]

In their search for principal causes of these alarming labor-market developments, economists initially focused on the role that global market integration could have played in explaining the rise in wage inequality.[4] Early empirical studies established a negative correlation between the volume of imports and the relative demand for less skilled workers.[5] This finding was interpreted as a manifestation of the Wolfgang F. Stolper and Paul

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[1] George E. Johnson (1997) documents the decline in the relative demand for less skilled U.S. workers during 1940–1993. Lawrence F. Katz and Kevin M. Murphy (1992), Murphy and Finis Welch (1992), and Chinhui Juhn et al. (1993), among others, have documented extensively the changes in the structure of U.S. wages. In addition, Marvin H. Kosters (1994), Gary Burtless (1995), Richard B. Freeman (1995), and David J. Richardson (1995) provide excellent overviews of the evidence.

[2] During the 1980's the real hourly wage of male workers with 12 years of schooling dropped by 20 percent (Freeman, 1995), and wage earnings differentials between high-school and college graduates in the United States rose by more than 10 percent (Eli Berman et al., 1994). Richardson (1995 footnote 1) cites several studies that have documented the rise in wage inequality in several advanced and less developed countries.

[3] See the *Economist*, September 28, 1996 p. 24, and Donald R. Davis (1998).

[4] Trade as a share of U.S. manufacturing shipments increased by about 30 percent during the 1980's with imports accounting for most of the increase (Berman et al., 1994).

[5] Murphy and Welch (1992), based on wage regressions, argue that trade has increased the wage differential between high-school and college graduates by about 4 to 5 percent. In addition, George J. Borjas and Valerie A. Ramey (1994) report a significant negative correlation between the relative wage of unskilled workers (high-school graduates versus college graduates) and net imports of durable goods as a percentage of GNP based on time-series evidence from the United States.

A. Samuelson (1941) theorem which states that a decline in the relative price of the imported good must reduce the return to the factor that is used intensively in its production. The Stolper-Samuelson theorem (henceforth abbreviated as SS) implies that increased trade between a developed (skilled-labor abundant) country and a developing (unskilled-labor abundant) country puts downward pressure on the relative wage of unskilled workers in the developed country.

This North–South trade explanation for increasing wage inequality in the North was later challenged, however, by several economists based on additional U.S. evidence. First, it was pointed out that domestic relative prices (of imported in terms of exported goods) have remained roughly constant despite the increase in the volume of trade.[6] Since the SS mechanism operates through changes in relative product prices, this evidence was interpreted as ruling out the trade explanation for increasing wage inequality.[7] Second, it was pointed out that the employment of skilled workers as a fraction of total employment has increased across all U.S. manufacturing industries, and that the shift in employment from less skilled to more skilled workers has occurred mostly within (as opposed to between) four-digit manufacturing industries.[8] Since changes in relative wages are associated with interindustry factor movements in the Heckscher-Ohlin-Samuelson trade model, the lack of interindustry resource movements was interpreted as further evidence against the trade explanation for rising wage inequality. Almost by default, unskilled-labor-saving technological change has become the dominant explanation for the rise in wage inequality.[9] This explanation is supported by the increased usage of computers in the workplace and by evidence that both R&D expenditures and the rate of technological change increased during the 1980's.[10]

In this paper, we will argue that the role of trade openness in reducing the relative wage of less skilled workers has been underestimated. Instead of interpreting the evidence using the traditional Heckscher-Ohlin-Samuelson trade model, where the focus is on product markets and trade is driven by differences in factor endowment proportions between countries, we present a new model of international trade where the focus is on financial markets and trade is driven by differences in knowledge between countries. We find that trade liberalization, by itself, can account not only for the observed rise in wage inequality, but also for the evidence on intraindustry skill upgrading and accelerating technological change.

In our two-country model of trade, individuals differ in their abilities within each country. An individual can choose not to acquire skills and spend her entire working life earning the unskilled wage. In this case, the individual's wage does not depend on her ability level. Alternatively, an individual can undergo "training" for an exogenous period of time without earning any income and become a skilled worker. Each skilled worker receives a wage

[6] There is no unanimous agreement among economists on the behavior of domestic relative prices during the 1980's. Lawrence and Matthew J. Slaughter (1993) found unchanged relative prices, whereas Jeffrey D. Sachs and Howard J. Shatz (1994) found a small decline in relative prices of less skilled-labor intensive goods.

[7] According to Alan V. Deardoff and Dalia S. Hakura (1994 p. 80), "those studies that have related the changes in factor prices to, say, the volume of trade cannot therefore be said to have been necessarily applying the Stolper-Samuelson theorem." Jagdish Bhagwati (1995) reflects the same view when he states: "Thus, I find it difficult to accept the argument . . . that almost all "quantity" data point towards trade as the source of the problem and that it is only 'prices' that do not conform. To say that it is to say that, in a production of *Hamlet,* only the Prince was missing, all else was fine!"

[8] During the 1980's, employment of production workers in U.S. manufacturing dropped by about 15 percent, whereas the employment of nonproduction workers increased by 3 percent (Berman et al., 1994). Employment of engineers in U.S. manufacturing increased by 55 percent, and employment of scientists increased by 12 percent (Shatz, 1996). Intraindustry (as opposed to interindustry) skill upgrading accounts for about 0.40 of the 0.55 share increase per year in U.S. manufacturing (Berman et al., 1994).

[9] Berman et al. (1994), Krugman and Lawrence (1994), Bhagwati (1995), and Davis (1996), among others, have proposed this explanation. The *Economist* (September 28, 1996 p. 28) reports that economists polled at a 1995 New York Federal Reserve conference concurred by a margin of four to one that technology was more important than trade in explaining widening wage inequality.

[10] Between 1979 and 1988 multifactor productivity growth increased by 40 percent relative to productivity growth in the previous two decades. R&D expenditure as a fraction of manufacturing shipments also experienced a sizeable increase (Berman et al., 1994). The annual flow of patent applications in the United States increased in the 1980's relative to the 1960's and 1970's as well (Samuel S. Kortum, 1997).

that depends positively on her ability. The decision to become a skilled worker is endogenous and depends on the relative wage of skilled workers. In equilibrium, individuals with high levels of ability become skilled and constitute the supply of skilled labor.

There is a continuum of structurally identical industries where firms produce final consumption goods using both unskilled and skilled labor. In each industry, firms can improve the quality of their products by investing in R&D. The arrival of innovations (higher quality products) is governed by a Poisson process whose intensity is proportional to R&D investment.[11] Because of free entry into R&D races, firms earn zero expected discounted profits. A firm that wins a R&D race is called a quality leader and is awarded a patent that enables the innovative firm to earn temporary monopoly profits from selling exclusively its state-of-the-art quality product in both countries. This patent expires when further innovation occurs in the same industry. Thereafter, the previously patented product can be competitively produced by firms in both countries. Thus, the "process of creative destruction" originally described by Joseph A. Schumpeter (1942) drives technological change in this model.

We assume that both countries (Home and Foreign) are structurally identical and impose the same ad valorem tariff on all imported goods, as in Luis Rivera-Batiz and Paul Romer (1991). These symmetry assumptions are obviously unrealistic, but are dictated by tractability considerations. They imply that all industries have the same skilled/unskilled labor employment ratio, and that the relative prices of all goods produced remain fixed. Therefore, the effects of trade liberalization on relative wages that occur through the traditional SS mechanism are excluded in some sense by assumption. A main insight of this paper is that trade openness can affect the wage inequality independently of changes in relative product prices. Even though both countries are structurally identical, state-of-the-art quality products are traded in equilibrium. Half of the world industries have Home quality leaders and half have Foreign quality leaders at each instant in time. These products are exported and compete against lower-quality domestically produced goods.[12] Thus, firms in both countries export those products that they alone know how to produce.

Global trade liberalization (caused by a reduction in the common tariff rate) increases the volume and the value of imports (and exports) as a percentage of each industry's shipments. However, because all industries are structurally identical by assumption, and products are perfect substitutes within each industry, relative final good prices are completely determined by quality differences and are unaffected by trade liberalization. Each quality leader charges a price that is proportional to her unit cost (the price of followers) with the factor of proportionality equal to a parameter capturing the size of each innovation (the quality increment). These are standard features in growth models based on quality improvements. A reduction in the common tariff increases the profit margin for each quality leader firm, but does not affect the price charged expressed in units of domestically produced goods.

In the Heckscher-Ohlin-Samuelson model, trade liberalization affects the relative prices of final goods and changes in relative prices induce changes in relative wages through the SS mechanism. In our model by contrast, because relative prices remain fixed in equilibrium, any effect of trade liberalization on relative wages must occur through some other channel. Lemma 1 in this paper establishes that another channel exists through which trade liberalization can influence relative wages: any change in the "relative price of innovation" (the reward for innovating relative to the current level of R&D difficulty) causes the relative wage of skilled

[11] We model product instead of process innovations because of their greater empirical relevance. Frederic M. Scherer (1984) reports that R&D targeting process innovations corresponds to a small fraction of company-financed industrial R&D: 26.2 percent when measured by the number of patents and 24.5 percent when measured by R&D expenditures. Therefore about 75 percent of company-financed R&D aims at product innovations.

[12] During the 1980's many U.S. industries faced import competition from higher-quality products produced abroad (e.g., semiconductors, automobiles, steel, machine tools). In all these industries technological competition between U.S. firms and their foreign counterparts resulted in the deterioration of U.S. international competitiveness. All these industries experienced changes in trade barriers during the 1980's.

workers to change. More precisely, Lemma 1 states that in the absence of factor-intensity reversals, an increase in the relative price of innovation increases the relative wage of skilled workers if and only if R&D is the skilled-labor intensive activity relative to manufacturing of final goods. Because the factor-intensity ranking between the two activities (R&D and manufacturing) determines which of the two factors (unskilled and skilled labor) is hurt when the relative price of innovation changes, Lemma 1 represents a Schumpeterian version of the SS mechanism.

Under the natural assumption that R&D is the skilled-labor intensive activity, Lemma 1 implies that trade liberalization hurts unskilled workers if it increases the profitability of innovating. Theorem 1 establishes that this is indeed the case: trade liberalization leads to increased wage inequality. Since R&D becomes more profitable as a result of trade liberalization, resources shift from manufacturing to R&D and the rate of global technological change rises (at least temporarily). In addition, a lower common tariff rate increases the fraction of the labor force that chooses to acquire skills, that is, trade liberalization leads to skill upgrading. Given our symmetry assumptions, both the resource shifts and the skill upgrading occur in each country and within each industry. Unlike the Heckscher-Ohlin-Samuelson model, lower tariffs do not lead to any movement in resources *across* industries and the increase in wage inequality occurs in *both* trading countries.

Given Theorem 1, it is clear that trade liberalization by itself can account for rising wage inequality as well as other previously mentioned economic trends. Within the context of the model, we briefly examine other possible reasons why wage inequality (and the relative price of innovation by Lemma 1) could have increased. An exogenous increase in the size of innovations leads to an increase in wage inequality but also increases the relative price of imported goods and reduces trade openness (the share of consumer expenditure that is spent on imported goods). An exogenous technical improvement in the provision of R&D services leads to an increase in wage inequality but leaves trade openness unaffected. Exogenous unskilled-labor-saving technological change in manufacturing (i.e., an exogenous increase in the skill intensity of manufacturing for any given relative wage ratio) has the same effect of increasing wage inequality but leaving trade openness unchanged. Furthermore, computer simulations reveal that exogenous unskilled-labor-saving technological change in manufacturing is also likely to reduce technological change and the relative size of the R&D sector if R&D mainly employs skilled workers and most of the labor force is unskilled. Thus these alternative reasons for rising wage inequality fail to account for the observed increase in trade openness (or the observed increase in the relative size of the R&D sector), leaving trade liberalization as the most likely single explanation that is consistent with the previously mentioned empirical evidence. Of course, in conjunction with trade liberalization, exogenous technological developments might have amplified some observed changes.

The rest of the paper is organized as follows: In Section I the model is presented and the long-run effects of global trade liberalization are derived. We also present evidence that supports the empirical relevance of Lemma 1 and computer simulations of the model to shed light on the magnitudes of the previously derived effects. Section II contains some concluding comments. Proofs of Lemma 1, Theorem 1, and details on data and calculations underlying Figure 2 are contained in Appendix A. The solution to the household optimization problem, the proof of existence and uniqueness of the steady-state equilibrium, and details on the simulation analysis are relegated to Appendix B, which is available from the authors upon request.

I. The Model

In this section, we present a two-country dynamic general equilibrium model of international trade and analyze its steady-state equilibrium properties. The model shares the same assumptions about consumer preferences and innovation processes with Dinopoulos and Segerstrom (1999) but differs in four important respects. First, building on earlier work on human capital acquisition by Ronald Findlay and Henryk Kierzkowski (1983) and Ian Borsook (1987), we explicitly model and endogenize the skill-acquisition process. Second, we allow both factors of production (unskilled and skilled labor) to be employed in both activities (R&D investment and manufacturing of final products). Third, we assume Cournot quantity competition in final goods markets instead of the usual Bertrand price competition in previous quality-ladder growth models. Finally, we assume that only state-of-the-art quality products are protected by patents instead of analyzing the case of infinite patent protection.

A. *Household Behavior and Skill Acquisition*

There is a continuum of households in each country indexed by ability $\theta \in [0, 1]$. All members of household θ have the same ability level equal to θ, and all households have the same number of members at each point in time. Each household is modeled as a dynastic family whose size grows over time at an exogenously given rate $n = \beta - \delta > 0$, where β is the birth rate and δ is the death rate. Each individual lives for an exogenously given period of time $D > 0$. Letting N_0 denote the number of members of each household at time $t = 0$, the population size in each country at time t is $N(t) = N_0 e^{nt}$. Because the number of births at time t equals the number of deaths at time $t + D$ [i.e., $\delta N(t + D) = \beta N(t)$ for all t], it follows that $\delta = n/(e^{nD} - 1)$ and $\beta = ne^{nD}/(e^{nD} - 1)$.

Family-optimization considerations determine the allocation of income across final goods, the evolution of consumption expenditure over time, and the decision whether to become skilled or enter the labor force as unskilled workers. In making these decisions, each family takes prices of final products, wages, and the interest rate as given.

Each individual knows her own ability level θ, as do all the firms that might potentially hire her. An individual can enter the labor force as unskilled and earn the wage w_L independently of her ability for the duration of her life D. Alternatively, an individual with ability θ can enter the labor force after spending an exogenously given period of time $T < D$ in "training" to become skilled. A skilled worker with ability $\theta \geq \gamma > 0$ earns a wage $(\theta - \gamma)w_H$ for a period $D - T > 0$, and does not earn any income during her period of training or apprenticeship. Thus skilled workers with higher ability levels earn higher wages. The parameter restriction $\gamma > 0$ implies, in effect, that not all individuals are capable of becoming skilled workers.[13] For simplicity, we assume that the training process does not require any real resources (other than the time of the trainee), and therefore the opportunity cost of becoming a skilled worker equals the discounted value of forgone unskilled wage income. We also assume that income is evenly shared within each family (between employed and trainees) so that, at each point in time, consumption expenditure is the same for each living member of a family.

The optimization problem of a family with ability θ is:

$$\max_{q_\theta} U_\theta \equiv \int_0^\infty N_0 e^{-(\rho - n)s} \log u_\theta(s)\, ds, \tag{1}$$

subject to the following constraints:

$$\log u_\theta(s) \equiv \int_0^1 \log\left[\sum_j \lambda^j q_\theta(j, \omega, s)\right] d\omega, \tag{2}$$

$$c_\theta(s) \equiv \int_0^1 \left[\sum_j p(j, \omega, s) q_\theta(j, \omega, s)\right] d\omega, \tag{3}$$

$$W_\theta(t) + Z_\theta(t) = \int_t^\infty N_0 c_\theta(s) e^{ns} e^{-[R(s) - R(t)]}\, ds. \tag{4}$$

Equation (1) is the discounted utility of a household with ability θ, where $\rho > 0$ is the constant

[13] Based on computer simulations of the model, we interpret γ as a "wage dispersion" parameter, since higher values of γ are associated with larger percentage differences between the wages of the highest- and lowest-paid skilled workers. In principle, γ can take any value between -1 and $+1$, but since the equilibrium dispersion in wages of skilled workers is unreasonably low for negative values of γ, we restrict attention to the $\gamma > 0$ case.

subjective discount rate, $n > 0$ is the exogenous rate of population growth, and $\rho - n > 0$ will be assumed to guarantee that the integral in (1) converges. Equation (2) defines the instantaneous utility function of each household member, where $q_\theta(j, \omega, s)$ denotes the quantity consumed by an individual with ability θ of a good with j improvements (innovations) in its quality in industry $\omega \in [0, 1]$ at time s. The parameter $\lambda > 1$ captures the size of each quality improvement and λ^j denotes the total quality of a good after j innovations. Equation (2) is standard in quality-ladder growth models with a continuum of industries. Equation (3) states that per capita consumption expenditure $c_\theta(s)$ at time s must equal the value of all final goods consumed, where $p(j, \omega, s)$ and $q_\theta(j, \omega, s)$ denote the price and quantity of a final product with j improvements in its quality in industry ω at time s. Finally, equation (4) is the standard intertemporal budget constraint. $W_\theta(t)$ is the family's discounted wage income from time t on, and $Z_\theta(t)$ is the value of the family's financial assets at time t. (In this model, some firms earn positive profits which are paid to the families that own these firms.) The right-hand side (RHS) of (4) equals the discounted value of family's consumption from time t to infinity, and $R(t) \equiv \int_0^t r(s)\, ds$ is the market discount factor with $\dot{R}(t) = r(t)$ denoting the instantaneous interest rate at time t.

Appendix B, which is available upon request, derives formally the solution to the family's dynamic optimization problem. This problem can be solved in three steps. First, maximizing subutility (2) subject to the expenditure constraint (3) yields a unit elastic demand function for the product(s) in each industry with the lowest-quality adjusted price. Because all products within an industry are perfect substitutes by assumption, only the product(s) with the lowest-quality adjusted price are purchased by consumers. Second, maximizing discounted utility (1) subject to the intertemporal budget constraint (4), we obtain the usual intertemporal optimization condition

$$\dot{c}_\theta(t)/c_\theta(t) = r(t) - \rho. \tag{5}$$

The differential equation (5) states that per capita consumption expenditure grows over time if and only if the market interest rate exceeds the subjective discount rate. Third, training/employment decisions are made to maximize each family's discounted wage income. An individual with ability θ born at time t undergoes training and becomes a skilled worker if and only if

$$\int_t^{t+D} e^{-[R(s)-R(t)]} w_L(s)\, ds < \int_{t+T}^{t+D} e^{-[R(s)-R(t)]} (\theta - \gamma) w_H(s)\, ds. \tag{6}$$

The left-hand side (LHS) of inequality (6) equals the discounted wage income of an individual from being employed as an unskilled worker and earning the wage w_L from time t until her death at time $t + D$. The RHS of (6) is the lifetime income of a skilled worker, who earns zero income during her training period and $(\theta - \gamma)w_H$ from time $t + T$ until time $t + D$, discounted to time t. Only when each member's discounted wage income is maximized can family utility be maximized.

The complexity of the model renders the analysis of equilibrium transition paths intractable and, therefore, we will focus on the model's steady-state equilibrium properties, where w_L, w_H, and c_θ are all constants over time. Then (5) implies that $r(t) = \rho$ for all t. Condition (6) can be used to determine endogenously the steady-state supply of unskilled labor. Because the RHS of (6) increases in θ, whereas the LHS is independent of θ, there exists a level of ability denoted by θ_0 such that (6) holds as an equality. All individuals with ability lower than θ_0 choose to remain unskilled, and all individuals with ability greater than θ_0 undergo training and then enter the labor force as skilled workers. Setting (6) to hold as an equality and solving for the steady-state value of θ_0, we obtain

$$\theta_0 = [(1 - e^{-\rho D})/(e^{-\rho T} - e^{-\rho D})] \times (w_L/w_H) + \gamma = (\sigma w_L/w_H) + \gamma, \tag{7}$$

where σ is the expression in square brackets in (7).

Because $\sigma > 1$ and $0 < \theta_0 - \gamma < 1$ always holds in equilibrium (as we will establish later), equation (7) implies that $(\theta_0 - \gamma)w_H > w_L$ and that $w_H/w_L > 1$. The wage of a skilled worker must always be higher than the wage of any unskilled worker. An increase in the duration of training T or in the relative wage of unskilled workers w_L/w_H increases the fraction of the population that chooses to remain unskilled θ_0. The supply of unskilled labor in each country at time t, $L(t)$, equals the number of individuals in the population that choose to remain unskilled:

$$L(t) = \theta_0 N(t). \tag{8}$$

The derivation of the steady-state supply of skilled labor at time t, $H(t)$, is slightly more complicated. A fraction $(1 - \theta_0)$ of each country's population train and become skilled workers, and therefore $(1 - \theta_0)N(t)$ individuals either work as skilled workers or are training to become skilled workers in each country at time t. In this subpopulation, the skilled workers are the older individuals, namely, those individuals that were born between $t - D$ and $t - T$:

$$\int_{t-D}^{t-T} \beta(1 - \theta_0)N(s)\, ds = (1 - \theta_0)\phi N(t),$$

where $\phi = (e^{n(D-T)} - 1)/(e^{nD} - 1) < 1$. The average skill level of workers that have finished training equals $[(\theta_0 - \gamma)/2] + [(1 - \gamma)/2] = (\theta_0 + 1 - 2\gamma)/2$, and therefore the supply of skilled labor, measured in efficiency units, at time t is given by

$$H(t) = (\theta_0 + 1 - 2\gamma)(1 - \theta_0)\phi N(t)/2, \tag{9}$$

where $\phi < 1$ depends only on the parameters of the model.[14]

It is obvious from equations (7), (8), and (9) that a decline in the relative wage of unskilled workers decreases θ_0 and $L(t)$, and increases $H(t)$, resulting in a rise of skilled labor abundance $H(t)/L(t)$ in each country. This is a standard result in models with variable factor supplies [e.g., Findlay and Kierzkowski (1983) and Borsook (1987)]. In the steady-state equilibrium, each country's factor supplies grow at the same rate as the population because θ_0 is constant over time:

$$\dot{H}(t)/H(t) = \dot{L}(t)/L(t) = \dot{N}(t)/N(t) = n.$$

B. *Product Markets and Trade*

There is a continuum of industries in each country indexed by $\omega \in [0, 1]$. In each industry, firms produce final consumption goods using both unskilled and skilled labor. The constant returns to scale production technology of firms is described by the following cost function:

$$A(w_L, W_H)Q, \tag{10}$$

where $A(w_L, w_H)$ is the unit-cost function and Q is the total output produced. $A(w_L, w_H)$ is an increasing and concave function with $A_L = \partial A/\partial w_L$ and $A_H = \partial A/\partial w_H$ denoting the unskilled and skilled labor requirements per unit of output, respectively. We assume that (10) is identical across industries and across different quality levels, and we will use the marginal (and average) cost of manufacturing in the Home country as the numeraire in the model:

$$A(w_L, w_H) = 1. \tag{11}$$

In each industry, we will refer to the firms that produce the state-of-the-art quality product as "quality leaders" and we will use the term "quality followers" to refer to firms producing a product one quality step below the highest-quality product. When a firm wins an R&D race and becomes a quality leader, it receives a patent to exclusively produce the new product and sell it to all consumers in the world. This patent expires when further innovation occurs in the industry. All products that are not protected by patents can be produced competitively in both countries.[15]

[14] Setting $D = \infty$ yields the special case of infinitely lived individuals where $\sigma = e^{\rho T} > 1$ and $\phi = e^{-nT} < 1$. Equations (7), (8), and (9) are not affected qualitatively, and the results of the paper hold in this case as well.

[15] The assumption that the technology of products without patent protection can be copied without any costs generates a competitive fringe of quality followers. This assumption simplifies the calculations, but in general, imitation involves considerable costs. Edwin Mansfield et al. (1981) provide evidence on the costs and speed of imitation

We assume that both countries impose a common ad valorem tariff τ on all imports. This common tariff is the only policy instrument used, and the tariff revenues are distributed to consumers in a lump-sum fashion. Firms take the common tariff as given when maximizing profits. Each quality leader has market power because it holds a patent protecting the state-of-the-art quality product in each industry. Unlike other models of growth through quality improvements that assume Bertrand price competition, we assume that each quality leader competes with quality followers in a Cournot fashion by setting quantities.[16]

Consider a Home quality leader that exports its product to the Foreign market (the analysis of the exporting behavior of a Foreign quality leader is identical because of structural symmetry between the two countries). Because unit costs of all followers are identical (and equal to unity), any positive tariff imposed by the Foreign government on imports from Home becomes prohibitive for Home followers. Given this market segmentation in inferior quality products, the Home quality leader competes in the Foreign market only with Foreign followers (and in the Home market only with Home followers).

Let Q_ℓ^* denote the output that the Home leader sells to Foreign consumers, let P_ℓ^* denote the price that Foreign consumers pay for the state-of-the-art quality product, and let Q_f^* denote the output of Foreign followers. International arbitrage requires that $p_\ell^*(1 + \tau) = P_\ell^*$ where p_ℓ^* is the after-tax price the Home leader receives from selling to Foreign consumers. In addition, goods are identical when adjusted for quality [see equation (2)] and therefore consumer arbitrage in the Foreign market implies that $P_\ell^* = \lambda p_f^*$, where $p_f^* = A(w_L, w_H) = 1$ is the price charged by Foreign followers (since free entry prevails in the inferior quality product market). In other words, the price that Foreign consumers pay for the state-of-the-art imported good cannot exceed λ times the price of the good produced by Foreign followers. The above reasoning leads to $p_\ell^*(1 + \tau) = \lambda = P_\ell^*$ and implies that an increase in the ad valorem tariff decreases the after-tax price of the Home quality leader. The market demand for a typical product is unitary elastic and therefore

$$(12) \quad [c^*(t)N^*(t)]/[p_\ell^*(1 + \tau)] = Q_\ell^* + (Q_f^*/\lambda),$$

where $c^*(t)$ is the economywide consumption per capita expenditure in the Foreign country. The RHS of (12) equals total quantity demanded expressed in units of the state-of-the-art quality product (i.e., one unit of Q_ℓ^* is equivalent to $1/\lambda$ units of Q_f^*).

Assumption (11) implies that the Home leader's profit flow from selling to Foreign consumers is:

$$(13) \quad \pi_\ell^* = p_\ell^* Q_\ell^* - Q_\ell^* = [c^*(t)N^*(t)Q_\ell^*]/[(1 + \tau) \times (Q_\ell^* + (Q_f^*/\lambda))] - Q_\ell^*,$$

where (12) has been used to substitute for p_ℓ^*. Maximizing (13) with respect to Q_ℓ^* yields the best reply function of the Home quality leader in implicit form:

$$(14) \quad \partial \pi_\ell^* / \partial Q_\ell^* = 0: \quad [c^*(t)N^*(t)Q_f^*]/[(1 + \tau)\lambda] = [Q_\ell^* + (Q_f^*/\lambda)]^2.$$

Because perfect competition prevails among Foreign followers, the zero-profit condition $p_f^* = 1$ determines the price of imports in the

for 48 industrial innovations. It can be shown that, even if patents do not expire with the discovery of higher-quality products, quality followers might not have incentives to engage in resource-using protection of their patents when other firms copy their products. Under Cournot competition between a quality leader and a quality follower, the profits of the latter are lower than those of a quality leader. Consequently, with sufficiently high costs of patent-infringement prevention, products of inferior quality will be copied even in the presence of infinite patents. Segerstrom et al. (1990) assume that patents have a finite and exogenously given duration in their model of North–South trade.

[16] The main results of the paper are unchanged if instead of Cournot quantity competition, the assumption of Bertrand competition in prices is adopted. In the latter case, only the state-of-the-art quality products are produced in equilibrium, and tariffs act as rent-shifting devises. A reduction in the common tariff rate increases the reward for innovating by increasing the profit margin under Bertrand competition. In this paper, we analyze the Cournot case because tariffs affect domestic production and can be interpreted as job-creating policy instruments in import-competing industries.

Foreign market $p^*_\ell(1 + \tau) = \lambda p^*_f = \lambda$. Therefore, we have

$$(15)\quad [c^*(t)N^*(t)]/\lambda = Q^*_\ell + (Q^*_f/\lambda).$$

Solving (14) and (15), we obtain the Cournot equilibrium quantity of imports Q^*_ℓ and domestic production Q^*_f in the Foreign market:

$$(16)\quad Q^*_\ell = c^*(t)N^*(t)(\lambda - 1 - \tau)/\lambda^2$$

$$(17)\quad Q^*_f = c^*(t)N^*(t)(1 + \tau)/\lambda.$$

Substituting (16) and (17) into (13) yields an expression for the equilibrium profit flow that a Home quality leader earns from exports:

$$(18)\quad \pi^*_\ell = [c^*(t)N^*(t)(\lambda - 1 - \tau)^2]/[(1 + \tau)\lambda^2].$$

Because a Home quality leader faces segmented markets, and does not pay the tariff rate τ when selling to Home consumers, the analysis of Cournot quantity competition in the Home market is identical to the analysis in the Foreign market where $\tau = 0$. The Home quality leader charges the price $p_\ell = \lambda$ to Home consumers, Home followers make zero profits from charging $p_f = 1$, and the quantities produced are given by

$$(19)\quad Q_f = c(t)N(t)/\lambda$$

$$(20)\quad Q_\ell = c(t)N(t)(\lambda - 1)/\lambda^2.$$

The profit flow earned by a Home quality leader from selling to Home consumers is obtained by setting $\tau = 0$ in (18):

$$(21)\quad \pi_\ell = c(t)N(t)(\lambda - 1)^2/\lambda^2,$$

where $c(t)$ and $N(t)$ are consumption expenditure per capita and population in the Home country. Structural symmetry across the two countries implies that $c(t) = c^*(t)$ and $N(t) = N^*(t)$. Therefore, each quality leader (Home or Foreign) exports the state-of-the-art quality product as well as sells to domestic consumers and earns the global profit flow

$$(22)\quad \pi = \pi^*_\ell + \pi_\ell = c(t)N(t) \times \left[\frac{(\lambda-1-\tau)^2}{(1+\tau)\lambda^2} + \frac{(\lambda-1)^2}{\lambda^2}\right].$$

The Cournot product market equilibrium has several interesting features. First, only the state-of-the-art quality products are traded. In other words, the quality of imported goods is always higher than the quality of domestically produced goods (the pattern of trade depends on whether a Home or a Foreign firm becomes a quality leader, an event that is purely random because the equilibrium level of R&D investment is the same in both countries). Second, all followers charge the same price $p_f = p^*_f = 1$ which is used as the numeraire, and all quality leaders charge the price $p_\ell = p^*_\ell(1 + \tau) = \lambda$ since they are constrained by domestic production of inferior quality goods that are perfect substitutes. Third, trade liberalization, caused by a reduction in τ, does not have any effect on relative prices (of domestically produced goods versus imported ones), but increases imports (exports) and the global profit flows of quality leaders. A reduction in the common tariff τ reduces domestic output and manufacturing employment in protected markets. The common tariff becomes prohibitive for $\tau \geq \lambda - 1$, and therefore we will assume that $0 \leq \tau \leq \lambda - 1$ in the subsequent analysis.

The value of imports (exports) as a percentage of consumption expenditure is an appropriate measure of trade liberalization that captures each country's openness:

$$(23)\quad (Q^*_\ell\lambda)/(Q^*_\ell\lambda + Q^*_f) = 1 - [(1 + \tau)/\lambda].$$

It immediately follows that

PROPOSITION 1: *Trade liberalization increases the openness of each country [measured by (23)], but has no effect on domestic and international prices.*

Because trade liberalization has no effect on domestic relative prices in either country, any effect that trade liberalization has on relative wages must operate through some channel other than the traditional Stolper-Samuelson mechanism. The previously established property that a reduction in the tariff rate τ directly increases the global profit flows of quality leaders will turn out to be significant.

C. *R&D Races*

There are sequential and stochastic R&D races in each industry $\omega \in [0, 1]$. These races result in the discovery of higher-quality final products. Both unskilled and skilled workers can engage in R&D activities. Workers are perfectly mobile across industries and activities within each industry (manufacturing and R&D), with unskilled workers employed in unskilled jobs and skilled workers doing skilled jobs. All firms participating in a R&D race use the same R&D technology and there is free entry into each race. Given the structural symmetry of the model, there are no gains from trading R&D services internationally and thus we solve for an equilibrium where R&D services are not traded between the two countries.

A firm i which engages in R&D in industry ω at time t and discovers the next higher-quality product with instantaneous probability $I_i(\omega, t)$ incurs the R&D cost flow

$$[B(w_L, w_H)X(\omega, t)]I_i(\omega, t), \tag{24}$$

where $B(w_L, w_H)$ is a standard unit-cost function derived from a constant returns to scale production function, and $X(\omega, t)$ is a function that captures the difficulty of conducting R&D. The term in square brackets equals the unit cost of R&D services $I_i(\omega, t)$.

We assume that the returns to R&D investment are independently distributed across firms, across industries, and over time. Therefore the industry-wide instantaneous probability of success in industry ω at time t is $I(\omega, t) = \sum_i I_i(\omega, t)$ in the Home country and $I^*(\omega, t) = \sum_i I_i^*(\omega, t)$ in the Foreign country. Thus the arrival of innovations in each industry is governed by a Poisson process whose intensity equals the global amount of R&D services $I(\omega, t) + I^*(\omega, t)$. Higher levels of R&D investment increase the expected frequency of innovations and result in a higher rate of technological change.

We consider two alternative specifications of $X(\omega, t)$, both of which rule out explosive growth and scale effects (see Charles I. Jones, 1995). In the first specification, R&D starts off being equally difficult in all industries [$X(\omega, 0) = 1$ for all ω], and the level of R&D difficulty grows over time according to

$$\dot{X}(\omega, t)/X(\omega, t) = \mu[I(\omega, t) + I^*(\omega, t)], \qquad \text{(TEG)}, \tag{25}$$

where $\mu > 0$ is a constant. This specification of R&D difficulty captures the notion that ideas that are easier to discover tend to be discovered earlier in time. We call the model resulting from (25) the TEG model because trade liberalization has only "temporary effects on growth." In the second specification, the difficulty of conducting R&D is proportional to the size of the global market measured by the number of consumers in both countries

$$X(\omega, t) = \mathrm{k}N(t), \qquad \text{(PEG)}, \tag{26}$$

where $\mathrm{k} > 0$ is a constant. This specification captures the idea that it is more difficult to introduce successfully new products and to replace old ones in a larger market. We call the model resulting from (26) the PEG model because trade liberalization has "permanent effects on growth."[17]

There is a global stock market that channels consumer savings to firms engaged in R&D. Because there is a continuum of industries with simultaneous R&D races, consumers can diversify completely the industry-specific risk and earn the equilibrium interest rate $r = \rho$. Each firm engaged in R&D issues a security that pays the flow of monopoly profits if the firm wins the R&D race and zero if it does not win the race. Let $v(\omega, t)$ denote the expected discounted profits of a successful firm (i.e., quality leader) in industry ω at time t. Because each quality leader is targeted by R&D firms in both countries that try to discover the next higher-quality product, the shareholder suffers a loss $v(\omega, t)$ if further innovation occurs. This event occurs with probability $[I(\omega, t) + I^*(\omega, t)]dt$, whereas the event of no innovation occurs with probability $1 - [I(\omega, t) + I^*(\omega, t)]dt$. Over a time

[17] Segerstrom (1998) proposed the TEG formulation of R&D difficulty given by (25). Dinopoulos and Peter Thompson (1996) provided micro foundations for (26) in a model of growth through variety accumulation.

interval dt, the shareholder of a stock issued by a successful R&D firm receives a dividend $\pi(t)\,dt$ and the value of the firm appreciates by $dv(\omega, t) = \dot{v}(\omega, t)\,dt$. Efficiency in the stock market requires that the expected rate of return of a stock issued by a successful R&D firm must be equal to the riskless rate of return r:

$$\frac{\dot{v}(\omega, t)}{v(\omega, t)}[1 - (I(\omega, t) + I^*(\omega, t))dt]dt - \frac{(v(\omega, t) - 0)}{v(\omega, t)}[I(\omega, t) + I^*(\omega, t)]dt + \frac{\pi(t)}{v(\omega, t)}dt = rdt.$$

Taking limits as $dt \to 0$, we obtain

$$(27) \quad v(\omega, t) = \frac{\pi(t)}{r + I(\omega, t) + I^*(\omega, t) - [\dot{v}(\omega, t)/v(\omega, t)]}.$$

Global profit flows earned by quality leaders are appropriately discounted using the instantaneous market interest rate and the instantaneous probability of being driven out of business by further innovation (the creative-destruction effect). Also taken into account in (27) are the capital gains that accrue to firms as the world economy grows.

Consider a firm i that is located in the Home country and engages in R&D. That firm chooses its R&D intensity $I_i(\omega, t)$ to maximize expected discounted profits

$$v(\omega, t)I_i(\omega, t)dt - B(w_L, w_H)X(\omega, t)I_i(\omega, t)dt.$$

Free entry into each R&D race drives these expected discounted profits down to zero and generates the following equilibrium condition:

$$(28) \quad S(\omega, t) \equiv v(\omega, t)/X(\omega, t) = B(w_L, w_H).$$

In the steady-state equilibrium, the reward for innovating $v(\omega, t)$ increases over time as the economy grows but $X(\omega, t)$ also increases over time as R&D becomes progressively more difficult. The ratio $S(\omega, t) \equiv [v(\omega, t)/X(\omega, t)]$ measures the reward for innovating relative to its cost and can be thought of as the "relative price" of an innovation. Equation (28) implies that there is a direct relationship between the relative price of innovation S and the relative wage of skilled workers w_H/w_L.

LEMMA 1 *(A Schumpeterian version of the SS mechanism): In the absence of factor-intensity reversals,*[18] *an increase in the relative price of innovation S:*

(i) *raises the wage of skilled labor w_H and lowers the wage of unskilled labor w_L if and only if R&D is the skilled-labor intensive activity; and*
(ii) *decreases the fraction of the population that chooses to remain unskilled θ_0 if and only if R&D is the skilled-labor intensive activity.*

PROOF:
See Appendix A.

Figure 1 illustrates the determination of wages for the case of R&D investment being the skilled-labor intensive activity relative to manufacturing of final products. Concavity of unit-cost functions $A(w_L, w_H)$ and $B(w_L, w_H)$ imply that equations (11) and (28) generate convex and downward-sloping curves in (w_L, w_H) space for any given value of the innovation price S. In the absence of factor-intensity reversals, the slope of the $B(w_L, w_H) = S$ curve is flatter than that of $A(w_L, w_H) = 1$, reflecting the assumption that R&D is the skilled-labor intensive activity. The unique intersection of the two curves at point E_1 determines the initial

[18] The assumption of no factor-intensity reversals is standard in the international trade literature and imposes restrictions on the functional forms of the two unit-cost functions. For instance, if the unit-cost functions correspond to Cobb-Douglas production functions, then there are no factor-intensity reversals; whereas in the case of two constant elasticity of substitution (CES) production functions with unequal elasticities of substitution, the unit-cost functions intersect at least twice resulting in factor-intensity reversals. Bhagwati and T. N. Srinivasan (1983 Ch. 5) provide more details on the role of this assumption in the traditional Heckscher-Ohlin-Samuelson trade model.

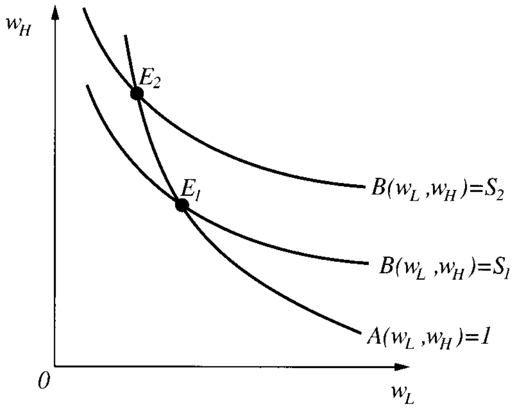

FIGURE 1. EQUILIBRIUM WAGES WITH R&D BEING THE SKILLED-LABOR INTENSIVE ACTIVITY

equilibrium wages w_H and w_L. An increase in the relative price of innovation from S_1 to S_2 raises the wage of skilled workers and reduces the wage of unskilled workers by shifting $B(w_L, w_H) = S$ upward [if and only if R&D is the skilled-labor intensive activity, that is, curve $B(\cdot) = S$ is flatter than curve $A(\cdot) = 1$]. The new equilibrium corresponds to point E_2 in Figure 1. The increase in the relative wage of skilled workers reduces θ_0 [see equation (7)] and increases the relative abundance of skilled labor [see equations (8) and (9)].

Is this Schumpeterian version of the Stolper-Samuelson (SSS) mechanism empirically relevant? To shed light on this issue, we plot in Figure 2 a skill price index (using the right axis) and an innovation price index (using the left axis) for the U.S. economy from 1963 to 1989. For the skill price index, we use the education skill price index in Juhn et al. (1993 Figure 8). It is an unweighted average of the male college–high-school log wage differential across experience levels based on data from the March *Current Population Survey*. We view this index as a reasonable proxy for the relative wage of skilled workers w_H/w_L. Appendix A provides details on the construction of an index designed to measure the relative price of innovation $S = v(t)/X(t)$. This index is the real price of U.S. assets (measured by the New York Stock Exchange Composite Index) divided by an index of R&D difficulty (based on U.S. patents for the TEG model and U.S. population for the PEG model). Figure 2 plots the relative price of innovation $S(t)$ index for the TEG specification. The graph of $S(t)$ for the PEG specification is visually indistinguishable from the one for the TEG specification (the correlation between the two series is 0.999), and it is not shown. The SSS mechanism implies a contemporaneous correlation between the skill price index and the innovation price index. As Figure 2 illustrates, there is indeed a strong positive correlation between these two price indices (0.8) and the two graphs have similar shapes. Thus, the linkage between the reward for innovating and wage inequality that is highlighted in this paper *does* appear to be empirically relevant.[19]

The SSS mechanism provides a novel explanation for the factor "bias" of technological progress. Whether an acceleration of across-the-board technological change (caused by an increase in the reward for innovating) contributes to more or less wage inequality depends precisely on the relative factor intensities of production and investment activities. Although production-labor-saving technological change is a sufficient condition that might have generated the observed increase in wage inequality over time, the above analysis suggests that it is hardly a necessary one.[20]

Trade liberalization puts upward pressure on S through its positive impact on the profit flows of all quality leaders. However, S is an endogenous variable that depends on virtually all the parameters of the model in addition to R&D difficulty variable X and global R&D investment $I + I^*$. This is the reason why the above result is stated as a lemma instead of as a theorem. The following subsection introduces the factor-market-equilibrium conditions which

[19] Interestingly, the following three international events are reflected in the graph of the innovation price index in Figure 2: first, the Bretton Woods system collapsed during the period 1968–1971; second, the start of the ongoing stock-market boom in 1979 coincided with the completion of the Tokyo round of trade negotiations which called for further trade-liberalization measures; and third, a larger-than-expected U.S. trade deficit coupled with turmoil in global financial markets generated the 1987 collapse of the stock market. These three episodes are all reflected in the shape of the education price index graph in Figure 2.

[20] In Figure 1, production-labor-saving technological change corresponds to a shift of the curve $A(w_L, w_H) = 1$ away from the origin and generates an increase in the relative wage of skilled workers if and only if R&D is the unskilled-labor intensive activity.

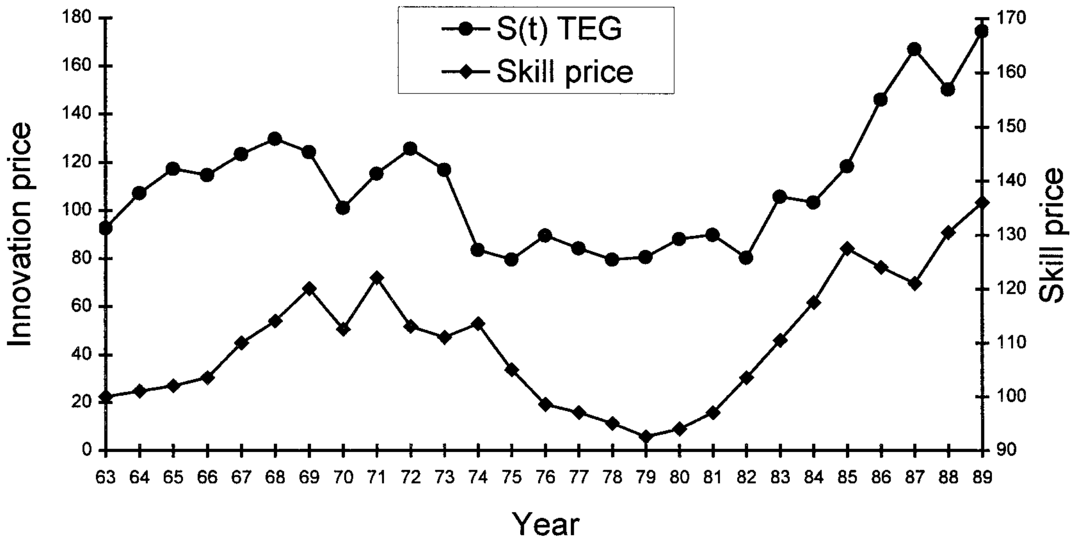

FIGURE 2. INNOVATION PRICE INDEX (LEFT AXIS) AND SKILL PRICE INDEX (RIGHT AXIS)

close the model and allow us to analyze the steady-state equilibrium effects of trade liberalization.

D. *Factor Markets*

We assume wage flexibility and perfect mobility of factors of production across industries and activities. These assumptions imply that the supply and demand for both skilled and unskilled labor are equalized at each instant in time. Because both countries are structurally identical, we concentrate on the derivation of equilibrium for the Home country. The supply of unskilled labor is given by equation (8), whereas the demand for unskilled labor consists of two components: unskilled labor employed in R&D and unskilled labor employed in manufacturing of final products. We consider the determination of each component of demand below.

The demand for unskilled R&D labor targeting industry ω at time t is derived from (24) using Shephard's lemma and equals $B_L(w_L, w_H)X(\omega, t)I(\omega, t)$ where $B_LX = (\partial B/\partial w_L)X$ is the unskilled-labor requirement per unit of R&D services, and $I = \sum_i I_i$ is industrywide R&D investment. Because R&D races occur in all industries and the measure of all these structurally identical industries equals one, B_LXI is also the economywide demand for unskilled labor employed by firms engaged in R&D.

Again using Shephard's lemma, we differentiate (10) with respect to w_L to obtain $A_L(w_L, w_H)Q(\omega, t)$, which equals the demand for unskilled manufacturing labor in industry ω at time t. Expression $A_L = \partial A/\partial w_L$ is the unskilled-labor requirement per unit of final output. The assumption of structurally identical countries implies that 50 percent of the world's quality leaders are Home firms and 50 percent are Foreign firms. In industries with a Home quality leader (exporting industries) total output produced equals $Q_f + Q_\ell + Q_\ell^*$, where Q_f is output produced by Home followers, Q_ℓ is the leader's output sold at Home, and Q_ℓ^* is the leader's output sold to Foreign consumers (exports). In industries with a Foreign leader, only protected Home followers produce and compete against imports. In Home import-competing industries production equals Q_f^*. Therefore, the total output produced in the Home country is

$$(29)\quad q = [(Q_f + Q_\ell + Q_\ell^*) + Q_f^*]/2$$
$$= c(t)N(t)(4\lambda - 2 + \tau(\lambda - 1))/(2\lambda^2),$$

where q is the "average" quantity of final output produced in each industry. The countrywide demand for unskilled labor in manufacturing is therefore $A_L(w_L, w_H)q$. Dividing the supply and the two components of demand for unskilled labor by $N(t)$, we obtain a per capita version of the full-employment condition for unskilled labor:

$$\theta_0 = A_L(w_L, w_H)(q/N(t)) + B_L(w_L, w_H)Ix, \tag{30}$$

where $q/N(t)$ is the per capita final output produced, and $x \equiv X(t)/N(t)$ is a measure of relative R&D difficulty.

The supply of skilled labor is given by equation (9) and the demand for skilled labor is derived using the same procedure as described above, the only difference being that the industrywide cost functions are differentiated with respect to the wage of skilled labor w_H. Therefore the corresponding per capita expression for the full-employment condition of skilled labor is

$$(\theta_0 + 1 - 2\gamma)(1 - \theta_0)\phi/2 = A_H(w_L, w_H)(q/N(t)) + B_H(w_L, w_H)Ix. \tag{31}$$

E. *Steady-State Equilibrium*

The two per capita full-employment of labor conditions (30) and (31) together with the two components of the SSS mechanism (11) and (28) constitute a system of four equations which determines the values of w_H, w_L, Ix, and q/N for any given values of S and θ_0. The structure of this system is identical to the traditional two-sector Heckscher-Ohlin-Samuelson economy that produces R&D services Ix, final output q/N, and faces a relative price of R&D investment expressed in terms of final goods which is equal to the relative price of innovation S. For a given θ_0, the supply of each factor is completely inelastic and the demand curves for skilled and unskilled labor are decreasing in w_H and w_L, respectively. Equation (7) determines the value of θ_0 as a function of the relative wage of unskilled workers, and the remaining equations determine the value of S.

We solve the model for a steady-state equilibrium where consumption per capita c, relative R&D difficulty x, effective R&D investment $I = I^*$, and wages w_L, w_H are all constant over time. Equation (5) then implies $r(t) = \rho$ and (7) implies that θ_0 is constant over time as well. Equations (22), (27), and (28) together imply that $\dot{v}/v = \dot{X}/X = n$. Straightforward substitutions yield the following expression for the average quantity of final output

$$q = B(w_L, w_H)(\rho + 2I + n)\Psi(\tau)X, \tag{32}$$

where $2I = I + I^*$ due to structural symmetry between the two countries and where

$$\Psi(\tau) \equiv q/\pi = \frac{[4\lambda - 2 + \tau(\lambda - 1)]}{2\left[\frac{(\lambda - 1 - \tau)^2}{(1 + \tau)} + (\lambda - 1)^2\right]} \tag{33}$$

is the inverse of profit flows per unit of average final output.[21] Ψ depends only on the level of protection and the size of innovations. It is obvious from (33) that $\Psi(\tau)$ increases in τ.

Equations (7) and (11) define implicitly each wage as a function of θ_0 with $dw_L/d\theta_0 > 0$ and $dw_H/d\theta_0 < 0$. Substituting (32) into the per capita full-employment of labor conditions (30) and (31) yields

$$\theta_0 = A_L(\theta_0)B(\theta_0)\Psi(\tau)(\rho + 2I - n)x + B_L(\theta_0)Ix, \tag{34}$$

$$(\theta_0 + 1 - 2\gamma)(1 - \theta_0)\phi/2 = A_H(\theta_0)B(\theta_0)\Psi(\tau)(\rho + 2I - n)x + B_H(\theta_0)Ix, \tag{35}$$

where the unit-resource requirements and $B(\cdot) = S$ depend on θ_0 through w_L and w_H. We have managed to reduce the model to a system of two equations in three unknowns, θ_0, x, and I. The third equation is provided by whether the TEG or the PEG specification of R&D difficulty is used.

Consider the TEG model first. Equation (25)

[21] Equation (32) is derived as follows: first, substitute π from (22) into the steady-state value of $v(t) = \pi/(\rho + 2I - n)$, which follows from (27). Then solve for consumption per capita c and substitute the resulting expression in (29) using (28).

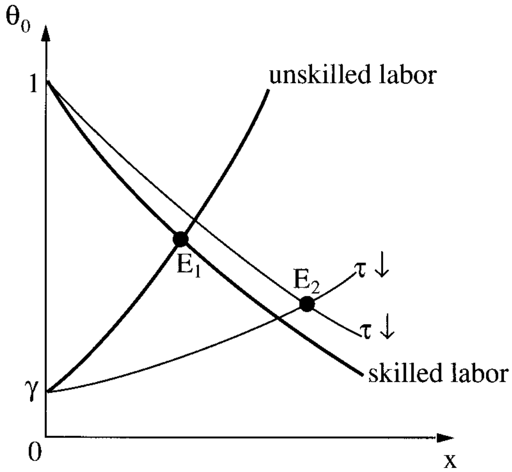

FIGURE 3. STEADY-STATE EFFECTS OF TRADE LIBERALIZATION IN THE TEG MODEL

implies that $\dot{X}/X = n = 2\mu I$. It immediately follows that the steady-state level of R&D investment $I = n/2\mu$ is completely determined by the exogenous rate of population growth n and the R&D difficulty growth parameter μ. If R&D does not become more difficult over time (i.e., $\mu = 0$), then there is no steady-state equilibrium with finite R&D investment (instead, positive population growth leads to exploding economic growth over time). With I pinned down, (34) and (35) represent a system of two equations in two unknowns which we can solve for a steady-state equilibrium.

These equations are illustrated in Figure 3. The vertical axis measures the fraction of the population that remains unskilled θ_0 and the horizontal axis measures the relative R&D difficulty x. The graph of equation (34) is the locus of x and θ_0 values that are consistent with full employment of unskilled labor when $I = n/2\mu$. This curve is upward sloping and crosses the vertical axis at $\theta_0 = \gamma > 0$ (see Appendix B, available upon request, for details). Starting from any point on this curve, an increase in θ_0 induced by an increase in the relative wage of unskilled workers reduces the demand for unskilled labor and increases its supply for any fixed level of x. Thus the LHS of (34) exceeds the RHS and an increase in x is required to balance both sides of equation (34) and to restore equilibrium in the unskilled labor market. The graph of equation (35) is the locus of x and θ_0 values that are consistent with full employment of skilled labor when $I = n/2\mu$. This graph is downward sloping and crosses the vertical axis at $\theta_0 = 1$ (see Appendix B, available upon request, for details). Starting from any point on this curve, an increase in θ_0 induced by an increase in the relative wage of unskilled workers increases the demand for skilled labor and reduces its supply for any given value of x. A reduction in x is required to reduce the RHS of (35) and restore equilibrium in the skilled labor market. The intersection of (34) and (35) at point E_1 determines the steady-state values of x and θ_0.

A sufficient but hardly necessary condition that guarantees the existence of a unique steady-state equilibrium in the TEG model is that

(36)
$$\lim_{\theta_0 \to \gamma^+} \frac{\theta_0 - \gamma + \sigma[B_H(\theta_0)/B_L(\theta_0)]}{\theta_0 - \gamma + \sigma[A_H(\theta_0)/A_L(\theta_0)]} < \infty$$

(see Appendix B, available upon request, for details). If the R&D skilled/unskilled labor ratio B_H/B_L does not approach infinity as w_L approaches zero and all workers become skilled, then condition (36) holds. This condition is satisfied for Cobb-Douglas production functions and for the class of CES functions where both inputs are essential for production.

Existence of a unique steady-state equilibrium can be similarly established for the PEG model. Equation (26) fixes the value of relative R&D difficulty $x = k$ for this model. Because the RHSs of (34) and (35) are increasing in R&D investment I, the graph of (34) is upward sloping and the graph of (35) is downward sloping in (I, θ_0) space as is illustrated in Figure 4. These curves intersect the vertical axis between $\theta_0 = \gamma > 0$ and $\theta_0 = 1$ (see Appendix B, available upon request, for details). A sufficiently low value of k or a sufficiently low value of $\rho - n$, together with condition (36), guarantee that these curves intersect in the positive orthant of (I, θ_0) space. Then, as is illustrated in Figure 4, the PEG model has a unique steady-state equilibrium (given by point E_1) and the steady-state value of θ_0 lies between γ and 1.

F. *Long-Run Growth*

The unique steady-state equilibrium in both the TEG and PEG models is associated with constant growth in each consumer's utility

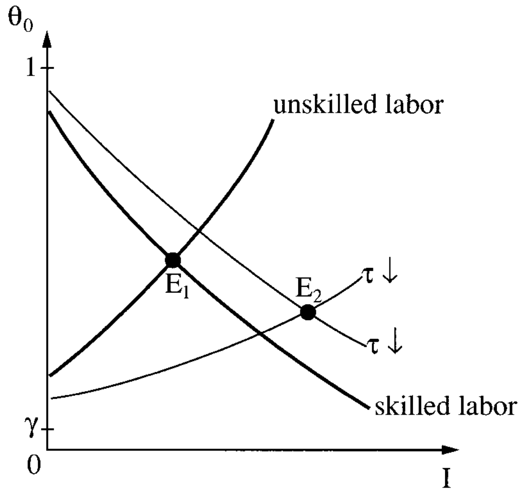

FIGURE 4. STEADY-STATE EFFECTS OF TRADE LIBERALIZATION IN THE PEG MODEL

over time. By substituting for consumer demand $c(t)/\lambda$ into a representative consumer's static utility function, we obtain $\log u(t) = \log c(t) - \log \lambda + \int_0^1 \log \lambda^{j(\omega,\, t)}\, d\omega$, where $j(\omega, t)$ is the number of quality improvements in industry ω at time t. The integral in this expression grows over time in the steady-state equilibrium as new higher-quality products are continuously being introduced. The value of this integral equals $2It \log \lambda$, where $\int_0^1 j(\omega, t)\, d\omega = 2It$ is the expected value of $j(\omega, t)$ and $2I$ is the steady-state intensity of the Poisson process that governs the arrival of innovations. Thus, in the steady-state equilibrium, each consumer's utility grows at the deterministic rate

$$(37) \qquad g_u \equiv \dot{u}(t)/u(t) = 2I(\log \lambda).$$

In the TEG model, the R&D intensity I depends only on parameters n and μ, and therefore trade liberalization has only transitional growth effects. In the PEG model, the R&D intensity I is proportional to the per capita costs of R&D [see equations (24) and (26)], and therefore is related to all the parameters of the model. Any shift in either or both curves in Figure 4 changes the long-run value of I and generates permanent growth effects. In both models, positive population growth does not drive the long-run R&D intensity or the per capita utility growth rate to infinity.

G. *Trade Liberalization, Relative Wages, and Economic Growth*

The main result in the paper is established by the following theorem.

THEOREM 1: *In the absence of factor-intensity reversals, a permanent increase in global trade liberalization caused by a reduction in the common tariff rate τ:*

(i) permanently reduces the wage of unskilled labor w_L and increases the wage of skilled labor w_H if and only if R&D investment is the skilled-labor intensive activity ($B_H/B_L > A_H/A_L$);
(ii) permanently decreases the fraction of the population that chooses to remain unskilled θ_0 if and only if R&D investment is the skilled-labor intensive activity ($B_H/B_L > A_H/A_L$);
(iii) temporarily increases the global rate of technological change $2I$, but has no effect on the long-run growth rate g_u in the TEG version of the model; and
(iv) permanently increases both the global rate of technological change 2I and the long-run growth rate g_u in the PEG version of the model.

PROOF:
See Appendix A.

Figures 3 and 4 illustrate the effects of trade liberalization on the steady-state equilibrium. Independently of whether the TEG or PEG specification is used, a reduction in the common tariff shifts both curves to the right. Theorem 1 implies that the new intersection E_2 lies below E_1 if and only if R&D is the skilled-labor intensive activity.

We are now in a position to state intuitively the general equilibrium effects of global trade liberalization. It is useful to decompose the effects of trade on resource allocation into those caused by price changes and into those triggered by changes in factor supplies. We focus on the more empirically relevant case of R&D being the skilled-labor intensive activity in order to facilitate the exposition. A reduction in the common tariff rate τ increases the profitability of R&D investment and raises the relative price of innovation S at the initial levels of relative R&D difficulty x and effective R&D investment I. It also increases the openness of the global economy measured by the share of trade in aggregate consumption (Proposition 1). Given the initial level of factor supplies, that is, for a fixed θ_0, an increase in S raises per capita R&D services Ix and reduces per capita average final output q/N as each country moves along its production possibility frontier in $(Ix, q/N)$ space [see the system of equations (11), (28), (30), and (31)]. Both skilled and unskilled workers move from production (manufacturing) to nonproduction (R&D) activities within each industry. The increase in R&D investment I raises the rate of technological change temporarily or permanently depending on whether the TEG or the PEG specification is assumed. Because the arrival of innovations is random in each industry, the observed acceleration of technological change need not be identical across industries. Finally, when R&D is the skilled-labor intensive activity, the increase in the relative price of innovation S reduces the demand for unskilled labor and increases the demand for skilled labor, resulting in increased wage inequality w_H/w_L in both countries.

When we allow for changes in factor supplies, the reduction in the common tariff rate τ has further ramifications. In response to the increase in wage inequality w_H/w_L, more workers choose to acquire skills and the fraction of the population that remains unskilled θ_0 declines. Holding S constant, the change in factor supplies generates Rybczynski-type effects by increasing further the supply of R&D services and by reducing the supply of per capita final output. This change can account for skill upgrading measured by the number of skilled workers as a fraction of total (manufacturing and R&D) employment in each industry (see footnote 8). The change in factor supplies reduces the initial impact of trade liberalization on wage inequality through the standard general equilibrium supply-based channels. Because all industries are structurally identical by assumption, both the skill upgrading and the shift in resources from manufacturing to R&D occur within all industries, all the above-mentioned effects of trade liberalization are global, and domestic relative prices remain unaffected throughout this process.[22]

Figure 5 illustrates the effects of trade liberalization on the wage earnings distribution by plotting wage income as a function of ability θ. The wage earnings curve consists of three connected linear segments: the horizontal segment corresponds to the wage income of workers with ability below θ_0 who choose to remain unskilled and receive the wage w_L; the vertical segment at θ_0 equals the difference between the wage earnings of skilled workers with ability θ_0 which is σw_L [see equation (7)] and the wage of unskilled workers w_L; and the upward-sloping segment shows the wage income of workers with ability greater than θ_0 who become skilled and receive a wage equal to $(\theta - \gamma)w_H$. Superscripts 1 and 2 denote the initial and final equilibrium values for the case of R&D being the skilled-labor intensive activity. Then trade liberalization leads to a drop in the wage income

[22] A large share of the technical change that occurred during the 1980's was in the form of Hicks-neutral innovations across all manufacturing industries. Lawrence and Slaughter (1993 Figure 10) show no correlation between the percentage changes in total factor productivity and the ratio of nonproduction to production workers employed in these industries in the 1980's. In addition, Sachs and Shatz (1994 p. 40) state that:

> evidently, biased technical change in the form of technical change that saves unskilled labor (inducing substitution of skilled for unskilled workers) was at work alongside neutral growth in total factor productivity.... In the postwar era, the proportion of nonproduction workers in total manufacturing employment increased steadily, from 16.6 percent in 1947, to 24.4 percent in 1960, 25.9 percent in 1970, 26.1 percent in 1978, and 31.0 percent in 1990.

Also, the predicted increase in the proportion of population that chooses to become skilled has been documented by Robert H. Topel (1997 p. 70) who states:

> as the college/high school wage premium rose through the 1960's, the fraction of (American) young men with some college climbed, peaking at 44 percent in the early 1970's, when the returns to college were at their highest level up to that time.... Starting around 1980, both the college wage premium and the proportion of young men attending college began to rise, the latter reaching an all-time high of 46 percent in 1992, when the returns to school were also at a record high.... As in Sweden, the American evidence is that the supply of skilled workers rises with the relative price of skill.

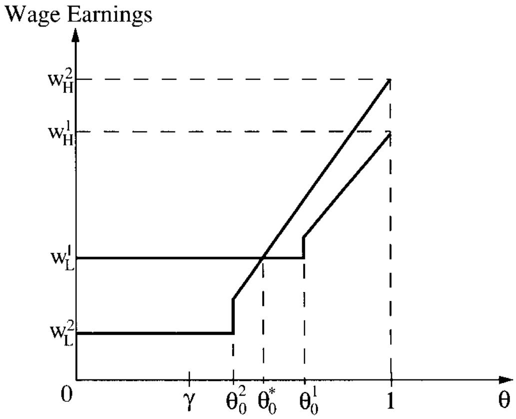

FIGURE 5. EFFECTS OF TRADE LIBERALIZATION ON THE WAGE EARNINGS DISTRIBUTION

earned by unskilled workers and a steeper wage earnings curve for skilled workers.

COROLLARY 1: *If R&D investment is the skilled-labor intensive activity, a sufficiently large reduction in the common tariff rate* τ *generates the phenomenon of immiserized skilled workers who earn less than what they would earn as unskilled workers at the initial level of the common tariff rate.*

In Figure 5, workers with ability levels between θ_0^2 and θ_0^* undergo training and become skilled, only to find out that they are earning less compared to their wage income before trade liberalization.[23]

We simulated the TEG version of the model and calculated the effects of an increase in trade openness from 3 percent to 12 percent, which is roughly consistent with the U.S. experience from 1970 to 1990 (Richardson, 1995). This change was caused by a number of factors including reductions in U.S. trade barriers, trade liberalization measures among U.S. trade partners, and reductions in transport costs (Krugman, 1995). In the simulation analysis, this increase in trade openness requires a reduction in the common tariff from 27 percent to 2.5 percent.[24] Appendix B, which is available upon request, provides details on the choice of parameters and robustness of the key simulated results.

As a result of trade liberalization, the model generates a long-run increase in the relative price of innovation S of about 5.6 percent and an increase in wage dispersion (measured by the average wage of skilled workers divided by the wage of unskilled workers) of about 4.5 percent (from 1.74 to 1.82). The wage of unskilled workers decreases by about 1 percent, and the fraction of the population that finishes "college" increases from 10 to 11 percent. These simulated results are similar in magnitude to those of Murphy and Welch (1992), who report a contribution of trade openness to the wage dispersion between high-school and college graduates of about 4 to 5 percentage points based on regression analysis. If the fraction of the population that chooses to remain unskilled is held

[23] Juhn et al. (1993 p. 421) point out that "for the lowest 40 percent of younger workers, real wages are lower in 1988 than for the corresponding group in 1964! Hence for two-fifths of all younger workers there has been no increase in economic opportunity as measured by weekly wage rates in about two and one-half decades." In addition, according to evidence reported in John Bound and George Johnson (1992 Table 1), a typical male worker with a high-school degree and less than 10 years of experience earned a real hourly wage of \$8.96 in 1979, whereas a male worker with the same experience who had some college education earned a lower real hourly wage of \$8.51 in 1988!

[24] We simulated the TEG version of the model under the following assumptions about the key parameters: $D = 40$, $T = 4$, $n = 0.01$, $\rho = 0.03$, $\lambda = 1.35$, $\mu = 0.15$, and $\gamma = 0.75$. In addition, we assumed that firms have Cobb-Douglas production functions that generate the following unit-cost functions: $A(w_L, w_H) = w_L^{0.85}w_H^{0.15}$ and $B(w_L, w_H) = w_L^{0.01}w_H^{0.99}$. Several of the parameter choices have transparent interpretations. Each individual has a working life of $D = 40$ years, and an "unskilled" high-school graduate becomes a "skilled" worker by spending $T = 4$ years in college. The population growth rate is one percent and each innovation represents a 35-percent improvement in product quality ($\lambda = 1.35$). The common subjective discount rate $\rho = 0.03$ was chosen to generate a 3-percent steady-state real interest rate and the R&D difficulty parameter $\mu = 0.15$ was chosen to generate a 2-percent steady-state growth rate when free trade prevails. Finally the dispersion parameter $\gamma = 0.75$ was chosen to guarantee that the fraction of the labor force in each country that becomes skilled is less than 25 percent, and to generate a reasonable level of dispersion in the wages of skilled workers. In equilibrium, the highest-paid skilled workers earn roughly twice as much as the lowest-paid skilled workers. For example, according to Michigan State University's Collegiate Employment Research Institute, in 1997 college graduates majoring in chemical engineering received the highest annual salary of \$42,758, whereas those majoring in journalism earned the lowest annual salary of \$22,102.

fixed at its initial equilibrium level $\theta_0 = 0.88$, then the contribution of trade openness to the relative price of innovation S doubles to about 10.5 percent, and the wage dispersion rises by about 12.5 percent (from 1.74 to 1.96). Overall, the graphs of the innovation price index and the education skill price index in Figure 2 coupled with the plausible simulated predictions support the empirical relevance of the model and suggest a promising direction for further empirical research regarding the contribution of trade to rising wage inequality.

Recently, exogenous technological change has become popular as a "residual" explanation of the stylized facts mentioned in the introduction (see footnotes 9 and 10). In the context of the present model, an exogenous increase in λ (a permanent increase in the size of innovations) corresponds to a demand-based increase in the rate of technological change. In addition, an exogenous decrease in k in the PEG model corresponds to a permanent increase in the efficiency of R&D investment. It is straightforward to establish that an increase in λ or a reduction in k increases the profitability of R&D and triggers the SSS mechanism that affects factor markets in exactly the same manner as a reduction in the common tariff.[25] However, exogenous technological change caused by an increase in λ increases the relative price of domestic goods and decreases economic openness [see equation (23)], contrary to the evidence on increased openness during the last three decades. Similarly, a reduction in k leaves both relative domestic prices and the openness of each country intact.[26] Consequently, exogenous technological change alone represents an unlikely explanation for all the previously mentioned stylized facts that characterized the global economy. However, in conjunction with trade liberalization, exogenous technological developments might have amplified some observed changes.

II. Conclusions

The analysis of this paper challenges several prevailing explanations for the global rise in wage inequality. Many economists have excluded trade openness as a cause of this change based on the fact that domestic relative prices have not declined (e.g., Lawrence and Slaughter, 1993). Other economists have adopted the view that competition from the South must have been responsible for the decline in the relative wage of unskilled workers (e.g., Adrian Wood, 1995).

A major insight of our analysis is that in imperfectly competitive markets, where Schumpeterian competition determines the pace of technological progress, changes in relative prices represent only one channel that links wages to trade liberalization. In these markets, the reward for innovating plays the same role as the domestic relative price in the conventional Heckscher-Ohlin-Samuelson model. Therefore, even if relative prices remain unaffected by trade liberalization (as in this model due to the assumed symmetry across industries and countries), a reduction in global tariffs that increases the profitability of R&D generates long-run (as opposed to purely transitory) changes in relative wages. Furthermore, the signs of these changes depend precisely on the Stolper-Samuelson condition of intensity rankings between R&D and manufacturing activities. We call the relationship between the relative price of innovation and the returns to factors of production a Schumpeterian version of the Stolper-Samuelson (SSS) mechanism because it adds an intertemporal component based on knowledge-generated trade to the traditional Stolper and Samuelson (1941) theorem.

[25] The parameter λ enters the model only through the function $\Psi(\tau)$, which is decreasing in λ. In the PEG model, the RHSs of (34) and (35) both increase in $x = k$. Therefore Theorem 1 applies to both an increase in λ and a reduction in k. It is worth noting that because $\dot{X}/X = n$ in the TEG model, a change in μ is not equivalent to exogenous technological change in R&D, but reflects a change in the long-run value of R&D investment.

[26] We have also analyzed the effects of exogenous technological change that increases the relative demand for skilled labor in manufacturing (i.e., an exogenous increase in the skill intensity of manufacturing for any given value of the relative wage ratio). This type of technological change has been associated with the increased use of computers in manufacturing. In the case of Cobb-Douglas manufacturing and R&D production functions, an exogenous increase in the skill intensity of manufacturing increases wage inequality, but it is also likely to slow technological change if R&D mainly employs skilled workers and most of the labor force is unskilled. In addition, this type of exogenous technological change leaves the openness of the economy unaffected.

Another new insight of the analysis is that production-labor or unskilled-labor biased technological change is not a necessary condition for a reduction of the relative wage of unskilled workers. Any increase in the profitability of innovation that results in higher R&D investment can affect adversely the wage income of unskilled workers when R&D is the skilled-labor intensive activity relative to manufacturing of final goods. The empirical relevance of the SSS mechanism is supported by U.S. time-series evidence presented in Figure 2, and simulation analysis indicates that trade liberalization by itself can account for a 4.5-percentage-point increase in wage inequality between U.S. college and high-school graduates. Consequently, the present paper suggests that North–North trade and financial markets (as opposed to North–South trade and product markets) are important components of an explanation for rising wage inequality in many advanced and developing countries.

An interesting direction for future research is to relax the assumption of structural symmetry across industries and countries, possibly by adding another sector without R&D-based technological change. Then presumably trade liberalization would affect relative wages through two channels: by influencing the domestic relative price of goods (the traditional Stolper-Samuelson mechanism); and by influencing the relative price of innovation.[27]

We are anxious to point out that our analysis does not advocate protection as a way to raise the living standards of unskilled workers. In the context of our model, protection increases the wage of unskilled workers (if R&D is skilled-labor intensive), but this corresponds to a level (as opposed to growth) effect. Protection slows (temporarily in the TEG model and permanently in the PEG model) the global innovation rate and all workers lose when the quality of each product is improved less frequently. In addition, protection retards the formation of human capital by increasing the fraction of the population that remains unskilled in the long run. Therefore, the income distribution level-type benefits of protection should be weighted against the intertemporal costs of lower growth in living standards and lower human capital formation. Welfare analysis can provide some policy guidelines, but the transitional dynamic properties of the model are complicated, and formal welfare analysis may be theoretically intractable.

[27] Several recent studies have provided alternative trade explanations for the decline in the relative wage of unskilled workers. Davis (1996, 1998) has examined the impact of trade and technology in a two-country global economy with one country experiencing unemployment based on an institutionally fixed minimum wage for unskilled workers. Robert C. Feenstra and Gordon H. Hanson (1996) have analyzed the impact of foreign investment and outsourcing on relative wages in a model of differentiated intermediate products. Bhagwati (1995) has proposed a North–North trade explanation based on shifts in international competitiveness that cause higher labor turnover and unemployment among less skilled workers. Also, Richardson (1995) emphasizes the dichotomy between consumption and investment goods in a model of trade, technology, and relative wages.

APPENDIX A

PROOF OF LEMMA 1:

Shephard's lemma yields the skilled-labor intensities in R&D and manufacturing:

$$\frac{\partial[B(w_L,\ w_H)X(\omega,\ t)I(\omega,\ t)]/\partial w_H}{\partial[B(w_L,\ w_H)X(\omega,\ t)I(\omega,\ t)]/\partial w_L} = \frac{B_H}{B_L} \text{ and } \frac{\partial[A(w_L,\ w_H)Q]/\partial w_H}{\partial[A(w_L,\ w_H)Q]/\partial w_L} = \frac{A_H}{A_L}$$

using (24) and (10). Consequently, R&D is the skilled-labor intensive activity if and only if $B_H/B_L > A_H/A_L$.

Totally differentiating equations (11) and (28) and solving for the change in each relative wage with respect to a change in the relative price of innovation yields

$$\text{(A1)} \qquad \frac{dw_L}{dS} = \frac{-A_H}{B_HA_L - A_HB_L},$$

$$\text{(A2)} \qquad \frac{dw_H}{dS} = \frac{A_L}{B_HA_L - A_HB_L}.$$

The denominator in (A1) and (A2) is positive (negative) if R&D (manufacturing) is skilled-labor intensive. The absence of factor-intensity reversals guarantees that the sign of the denominator is the same for all values of the relative wage ratio. This completes the proof of part (i).

Differentiate equation (7) totally and substitute (A1) and (A2) to obtain

$$\text{(A3)}\qquad \frac{d\theta_0}{dS} = \frac{\sigma}{w_H}\frac{dw_L}{dS} - \frac{\sigma w_L}{w_H^2}\frac{dw_H}{dS} = -\frac{\sigma}{w_H^2(B_H A_L - A_H B_L)},$$

where $A = A_L w_L + A_H w_H = 1$ has been used as well. This completes the proof of part (ii).

The Relative Price of Innovation: We constructed an index of the relative price of innovation $S(t) \equiv v(t)/X(t)$ for the United States over the period 1963–1989 by making several restrictive but reasonable assumptions. Assuming that the stock-market valuation of R&D investment relative to other tangible and intangible assets remains constant over time, we used the New York Stock Exchange Composite Price Index divided by the price of consumer durables to obtain an index of $v(t)$. Data for the calculations of the real price of assets are from the *Economic Report of the President* (1995 Tables 96 and B-4). Bronwyn H. Hall and Robert E. Hall (1993) conclude that R&D intensive firms have enjoyed higher-than-average stock-market values in the United States during the period 1964–1990. They also report that, although the stock-market valuation of R&D relative to other assets (physical and intangible) varies over time, these changes are not statistically significant. We used the price index of consumer durables because these industries tend to be more concentrated and more R&D intensive.

The measurement of R&D difficulty $X(t)$ followed closely equations (25) and (26). The annual number of patents granted by the U.S. Patent Office to U.S. inventors was used as a proxy for effective R&D investment Kortum (1997 Appendix A) has details on the construction of the annual patent series, and we are indebted to him for providing the data. Parameter μ in equation (25) was chosen to equalize the average annual rate of U.S. population growth over our sample period (of about 1 percent) to the average annual number of patents (of about 43,700). In a steady-state equilibrium, relative R&D difficulty $x \equiv X(t)/N(t)$ is constant over time and equation (25) becomes $n = 2\mu I$. Assuming that the U.S. accounts for half of the world's patents, this reasoning provides a plausible value of the parameter μ. Using this value of μ and equation (25), we calculated the annual growth rate of $X(t)$. The computed growth rates were used to generate an index of $X(t)$ for the TEG version of the model starting with the value of 100 for 1963. The level of R&D difficulty for the PEG specification was calculated using the U.S. population (measured in millions) in accordance with equation (26) where parameter k was chosen to normalize the series to 100 for 1963. Both specifications generated almost identical indices of R&D difficulty that increase by about one percentage point annually to approach the value 130 in 1989. An index of the real value of innovation was constructed for each of the two specifications by dividing the real value of assets by the level of R&D difficulty.

PROOF OF THEOREM 1:

Because the tariff τ enters (34) and (35) only through the function Ψ, it is sufficient to analyze how each curve shifts as a result of a reduction in Ψ. Trade liberalization (a decrease in τ) causes Ψ to decrease, given (33). A reduction in Ψ increases the value of x in the TEG model (or I in the PEG model) for any given value of θ_0 in both equations (34) and (35). Therefore both curves shift to the right as a result of trade liberalization. Differentiating (34) and (35) with respect to Ψ and x holding θ_0 fixed yields

$$\text{(A4)}\qquad \left.\frac{-dx}{d\Psi}\right|_{(34)} = \frac{B[\rho + (n/\mu) - n]x}{B\Psi[\rho + (n/\mu) - n] + \dfrac{B_L n}{A_L 2\mu}},$$

$$\text{(A5)}\qquad \left.\frac{-dx}{d\Psi}\right|_{(35)} = \frac{B[\rho + (n/\mu) - n]x}{B\Psi[\rho + (n/\mu) - n] + \dfrac{B_H n}{A_H 2\mu}}.$$

It is obvious from inspection of (A4) and (A5) that only the last term in each denominator differs. Therefore, the RHS of (A4) is larger than the RHS of (A5) if and only if $B_L/A_L < B_H/A_H$. Because the RHSs of (34) and (35) are increasing and linear in I, one can obtain the same result for the PEG specification. Thus, in both models a reduction in the common tariff τ reduces θ_0 if and only if R&D is the skilled-labor intensive activity.

Equations (7) and (11) define w_L and w_H as functions of θ_0. Totally differentiating these equations using Euler's theorem ($A_L w_L + A_H w_H = A$) yields

$$\text{(A6)} \qquad \frac{dw_L}{d\theta_0} = \frac{A_H w_H w_L}{\theta_0 - \gamma} > 0;$$

$$\frac{dw_H}{d\theta_0} = -\frac{A_L w_H w_L}{\theta_0 - \gamma} < 0.$$

Expressions (A6) together with the result that trade liberalization reduces θ_0 if and only if R&D is the skilled-labor intensive activity prove formally parts (i) and (ii) of Theorem 1. Parts (iii) and (iv) follow from the result that trade liberalization shifts both curves in Figures 3 and 4 to the right and results in a permanent increase in x or I, depending on whether the TEG or the PEG specification is used. In the case of the TEG model, a higher long-run value of $x \equiv X/N$ implies that X has to grow faster than N temporarily, and given (25), this means that the R&D intensity I has to increase temporarily.

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