A Schumpeterian Model of the Product Life Cycle

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This paper presents a dynamic general equilibrium model of North–South trade in which research and development races between firms determine the rate of product innovation in the North. Tariffs designed to protect dying industries in the North from Southern competition reduce the steady-state number of dominant firms in the North, reduce the rate of product innovation, and increase the relative wage of Northern workers. (*JEL* 411, 111)

In his celebrated "product life cycle" paper Raymond Vernon (1966) argued that many products experience cycles. These products are initially discovered and produced in developed countries (the North), and exported to less developed countries (the South). As the techniques of production become more standardized, production shifts to less developed countries due to lower labor costs. These older products are then exported back to developed countries.

The product-life-cycle hypothesis has attracted considerable attention among international-trade theorists in recent years. In this literature, the rate at which an individual firm discovers and successfully markets new products is either treated as exogenously given (Paul Krugman, 1979; David Dollar, 1986, 1987) or as a "deterministic" function of the firm's expenditures on new product development (Robert Feenstra and Kenneth Judd, 1982; Thomas Pugel, 1982; Barbara Spencer and James Brander, 1983; Leonard Cheng, 1984; Richard Jensen and Marie Thursby, 1986, 1987). Thus, from the individual firm's perspective, successful product innovation is either effortless or guaranteed by large expenditures on new product development. In contrast, Joseph Schumpeter (1942) stressed that firms compete with each other to successfully introduce new products. The recent industrial-organization literature has followed Schumpeter's lead (see, e.g., Glen Loury, 1979; Tom Lee and Louis Wilde, 1980; Jennifer Reinganum, 1982). In these research and development (R&D) models, there are losers as well as winners because a firm can spend substantial resources on new product development only to find that another firm has discovered and patented the new product first.

In this paper, we construct a dynamic, general equilibrium model of North–South trade that combines the product-life-cycle hypothesis with Schumpeter's (1942) description of product innovation. We model each R&D race as an "invention lottery" in which the probability of winning the race is proportional to resources devoted to R&D by each firm. The duration of each R&D race is a deterministic decreasing function of the amount of aggregate resources devoted to R&D. Every time a new product is discovered, a new R&D race between firms in the North begins. The winner of each R&D race earns dominant firm profits for an exogenously given patent period, after which perfect competition prevails. Firms in the North choose how much labor to hire for R&D by maximizing expected discounted profits, and consumers maximize their discounted lifetime utility.

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We show that a unique steady-state equilibrium exists in which the number of new products, consumer expenditures, and assets are all constant over time. In the steady state, Northern workers earn higher wages than their Southern counterparts if the South has a sufficiently large fraction of the world labor force. Moreover, the pattern of trade continuously changes with each product initially being exported and then later imported by the North.

Endogenizing the rate of technological change generates some surprising comparative steady-state results in our model. When wages in the North and in the South are equal, an increase in the patent length (or a decrease in the rate of technology transfer to the South) increases the rate of product innovation in the North. This result is consistent with the partial-equilibrium industrial-organization literature on R&D competition, because an increase in the patent length increases the reward for winning an R&D race. However, when Northern workers earn higher wages than Southern workers, an increase in the patent length *decreases* the rate of product innovation in the North. The increase in the patent length, by itself, increases the reward for innovative activity, but Northern wages rise more than enough to offset this effect.

Unlike the previously mentioned studies, we also examine the effects of tariffs designed to protect dying industries in the North from Southern competition. When Northern workers earn higher wages than Southern workers, we find that an increase in the number of industries being protected in the North leads to higher relative wages for Northern workers and a slower rate of innovation. Thus, we are able to theoretically link protectionist trade policies with slower economic growth.

The rest of this paper is organized as follows: In Section I, the dynamic general equilibrium model of North–South trade is presented. In Section II, we characterize the steady-state equilibrium of the model. The relationship between relative labor endowments and steady-state relative wages is explained in Section III. Section IV analyzes the effects of changes in patent length and tariff protection on the steady-state equilibrium. Finally, our conclusions are presented in Section V.

I. The Model

Consider a world consisting of two countries: the North and the South. Let $\bar{L}^{\mathrm{N}}$ and $\bar{L}^{\mathrm{S}}$ be the aggregate endowments of labor in the North and in the South, respectively. These labor endowments do not change over time.

In this world, there is a countably infinite set of product $N \equiv \{1,2,3,\dots\}$. At any point in time $t \in [0,\infty)$, these products can be partitioned into three sets: the set of products that any firm in the world knows how to produce, the set of products that only one firm in the world knows how to produce, and the set of products that no firm in the world knows how to produce. Firms that produce products in the second set are called dominant firms.

At time t, every firm that knows how to produce product $j \in N$ has the same production technology. Constant returns to scale prevail in production, with one unit of labor producing one unit of product j. Labor is the only factor of production, and all workers in the world are equally productive. Factors of production are not mobile internationally.

At time $t=0$, there are n products for which the production technology is common knowledge, and the remainder of the products have unknown production technology. Time $t=0$ represents the beginning of a sequence of R&D races between firms in the North. Only workers in the North are capable of doing R&D-type work, and therefore only firms in the North compete in these R&D races. Every time an R&D race in the North ends, a new R&D race immediately begins. At the beginning of the jth R&D race, each firm i in the North must decide how much labor L_{ij}^{R} to devote to R&D. This choice by firm i represents a commitment to employing L_{ij}^{R} units of R&D labor for the duration of the jth R&D race. The firm that wins the jth R&D race becomes the sole producer in the world of product $n+j$ for a time period of length

$T > 0$. After this "patent" expires, the production technology for product $n+j$ becomes common knowledge.[1]

We model each R&D race as an "invention lottery." Each of the L_j^R worker-researchers participating in the jth R&D race is equally likely to discover product $n+j$ at time $\hat{t}_j = h(L_j^R)$ after the beginning of the jth R&D race, where $L_j^R \equiv \sum_i L_{ij}^R$ is the aggregate labor devoted to R&D. Thus, at the end of the jth race, nature draws one of the L_j^R "lottery tickets" and one of the L_j^R worker-researchers discovers the new product. The firm that employs the winner earns dominant firm profits until its patent expires. Firm i wins the jth race with probability L_{ij}^R / L_j^R.

By modeling the R&D process as an "invention lottery," we capture two features of R&D races that we feel are important. First, individual firms investing in R&D face an uncertain return; there are winners and losers. In contrast, with other models of technological change and international trade (see, e.g., Jensen and Thursby, 1986; Gene Grossman and Elhanan Helpman, 1989; Feenstra and Judd, 1982), a firm is not guaranteed success in developing a new product by spending some fixed sum of money on product development. Secondly, new products tend to be discovered faster and at a greater discounted cost, as more resources are devoted to R&D [this is implied by properties of the $h(\cdot)$ function to be specified shortly]. There is an intertemporal trade-off associated with R&D activity. From the individual firm's perspective, as it spends more money on R&D (a flow expenditure), its possibility of winning the race increases, other firm's probabilities of success decline, and the race ends sooner.[2]

In this model, at each point in time t, wages for workers in each country are determined by competitive market forces. We set the equilibrium wage rate for workers in the South equal to one and let w denote the equilibrium relative wage of workers in the North. Both production workers and R&D workers in the North are paid the same wage w.

In addition to the absence of international labor mobility, we assume that production of goods protected by patents takes place only in the North. In other words, Southern firms can produce a good only after its patent protection has expired. Possible institutional justification for this assumption would be that enforcement of patent laws in the South is considerably weaker than in the North and the labor market within the South constitutes an effective channel of technology diffusion. Thus, in the absence of effective patent protection in the South, a Northern dominant firm producing in the South faces the risk that some of its workers might establish another firm manufacturing the same product.[3]

Infinitely lived consumers maximize total lifetime utility. Each consumer has an identical time-separable utility function

$$U \equiv \int_0^\infty e^{-\rho t} \log u(\cdot)\, dt \tag{1}$$

where $\rho > 0$ is the constant subjective discount rate and $u(\cdot)$ is an instantaneous utility function.[4] We adopt a particular

[1] T is inversely related to the rate of technology transfer in Krugman (1979) and Jensen and Thursby (1986). "Patents" need not be given a literal interpretation. The patent length T serves as a proxy for all relevant factors that impede technology transfer between the North and South.

[2] The deterministic length $\hat{t} = h(L^R)$ of each R&D race is admittedly artificial, but as will become clear, the main results in the paper are driven by factor market constraints, which would be present whether the length of each R&D race were deterministic or stochastic. To analyze tractably the effects of commercial policy in a general equilibrium setting, we also abstract from certain interesting features of R&D races (established-firm advantages, variable R&D expenditures over time, imitation in spite of patent protection, etc.) that have been extensively studied in the partial-equilibrium industrial-organization literature.

[3] Allowing dominant firms to produce in the South could generate multinational firms along the lines proposed by Grossman and Helpman (1989). Multinational activity in our model results in the wage being equalized between the North and South unless all Northern labor is engaged in R&D.

[4] The same form of total lifetime utility is used by Grossman and Helpman (1989).

form of $u(\cdot)$,

$$(2)\quad u(x_1,x_2,x_3,\dots)\equiv\prod_{j=1}^{n}\left(\sum_{i=0}^{\infty}\alpha^i x_{j+ni}\right).$$

This is a generalized symmetric Cobb-Douglas utility function where n can be interpreted as the number of product groups. Since products within each group are perfect substitutes, we call this the CDP (Cobb-Douglas with perfect substitutes) utility substitutes) utility function. Product group j ($j=1,2,3,\dots,n$) consists of products j, $n+j$, ...; and $\alpha>1$ represents the extent to which each new product improves upon existing products in the same product group.

To illustrate the effect of product innovation on consumer utility, suppose that initially there are n products available for consumption. Given time separability, consumers are, in effect, maximizing the utility function $\tilde{U}\equiv x_1x_2x_3\dots x_n$ at that instant in time. The discovery of product $n+1$ means that consumers are now, in effect, maximizing the utility function $\tilde{U}\equiv(x_1+\alpha x_{n+1})x_2x_3\dots x_n$. If the equilibrium prices of products 1 and $n+1$ both equal one, which would be the case if both products 1 and $n+1$ were produced competitively, then no consumer would purchase product 1 (given $\alpha>1$), and it would become obsolete. Thus, new products substitute perfectly for old products, and product innovation in our model takes the form of superior products replacing inferior products.[5]

We assume that there is a capital market in the North which supplies the savings of Northern consumers to firms engaged in R&D. The equilibrium interest rate $r(t)$ clears the capital market at each point in time t. Firms borrow funds from this market to pay workers as the R&D is done. Each firm issues a risky security that yields a positive return if it wins and a negative return if it loses an R&D race. Assuming risk neutrality and perfect competition in R&D, Northern firms enter each R&D race until expected discounted profits are driven to zero. Southern consumers are not allowed to participate in the capital market, and therefore at each instant of time, their income equals their expenditure. If this assumption is relaxed, then Southern savings would end up financing part of the North's R&D expenditure, a result that is contrary to empirical evidence.[6]

Free trade is assumed to exist between the North and the South throughout time, and products are assumed to be nonstorable. Furthermore, at any time t, perfect competition prevails in the market for each product whose patent has expired. Thus, the market price for all such products equals the marginal cost of production in the South (one). Given the consumer preferences, one unit of product j gives each consumer as much utility as α units of product $j-n$. When both products are competitively produced and sell at the same market prices (equal to one), the competitive market for product j renders product $j-n$ obsolete.

The endowment of labor in the North $\bar{L}^{\mathrm{N}}$ is assumed to be sufficiently small so that, even if all the workers in the North did R&D-type work, the number of dominant firms would be less than the number of product groups n. That is, $h(\bar{L}^{\mathrm{N}})n>T$. This condition guarantees that there are never two dominant firms producing products in the same product group.[7] At time t, the dominant firm producing product j must

[5]Nancy Stokey (1988) models product replacement in a different context. The rest of the product-life-cycle literature has treated product innovation as being the introduction of greater variety.

[6]All the comparative steady-state results concerning the effects of changes in labor endowments, patents, and tariffs on the number of dominant firms, the rate of innovation, relative wages, and world assets would be unaffected if the capital market were international. Nor would the magnitudes of these variables be affected. However, the distribution of world assets between the North and the South and the pattern of trade in the steady state would change.

[7]Even if innovations did not occur in the previously described sequence, all the results in the paper would be unaffected if product j is only discovered when product $j-n$ is competitively produced. For example, it is possible that certain groups do not experience any innovation at all.

compete only against a competitive fringe of firms producing product $j-n$.

The dominant firm and firms in the competitive fringe simultaneously set prices, and we solve for a Bertrand-type Nash equilibrium. Let E^{W} denote instantaneous world expenditure. Given the instantaneous CDP utility function, world expenditure at time t on products in product group j is E^{W}/n. With the equilibrium price of one being charged by firms in the competitive fringe, the dominant firm has zero sales if it charges a price p^{d} greater than α. On the other hand, the competitive fringe has zero sales if the dominant firm charges a price p^{d} less than α. If $p^{\mathrm{d}}=\alpha$, then consumers are indifferent between spending E^{W}/n on product j and spending E^{W}/n on product $j-n$. We assume that all the indifferent consumers buy from the dominant firm (all rules for rationing the demand of indifferent consumers among firms are somewhat arbitrary). Then dominant-firm profits are

$$\text{(3)}\quad \pi^{\mathrm{d}}(p^{\mathrm{d}}) = \begin{cases} 0 & \text{if } p^{\mathrm{d}}>\alpha \\ (p^{\mathrm{d}}-w)E^{\mathrm{W}}/p^{\mathrm{d}}n & \text{if } p^{\mathrm{d}}\le\alpha. \end{cases}$$

These profits are clearly maximized where $p^{\mathrm{d}}=\alpha$. Thus, in the Nash noncooperative equilibrium in prices that we examine in the rest of this paper, each dominant firm produces $q^{\mathrm{d}}\equiv E^{\mathrm{W}}/\alpha n$ and earns profits

$$\text{(4)}\qquad \pi^{\mathrm{d}}\equiv\frac{E^{\mathrm{W}}}{n}\left(\frac{\alpha-w}{\alpha}\right).$$

The competitive fringe constrains each dominant firm from charging prices higher than α.

Several restrictions are placed on the $h(\cdot)$ function that defines the R&D technology. First, $h(\cdot)$ is assumed to be continuously differentiable with $h'(\cdot)<0$. This guarantees that product innovation occurs at a faster rate when firms in the North devote more resources to R&D. Second $\bar{h}\equiv h(0)<+\infty$; that is, some product innovation occurs even if no resources are devoted to R&D. Third, $h(L^{\mathrm{R}})>0$ and $h''(L^{\mathrm{R}})\ge 0$ for all $L^{\mathrm{R}}>0$; that is, no matter how much labor is devoted to R&D, innovation never occurs instantaneously. Fourth,

$$\text{(5)}\qquad \frac{d}{dL^{\mathrm{R}}}L^{\mathrm{R}}\left(e^{\rho h(L^{\mathrm{R}})}-1\right)>0.$$

Notice that $\int_{-h(L^{\mathrm{R}})}^{0} wL^{\mathrm{R}}e^{-\rho t}dt = wL^{\mathrm{R}}(e^{\rho h(L^{\mathrm{R}})}-1)/\rho$ is the discounted labor cost of developing a new product (discounted to the end of the R&D race) when the market interest rate $r(t)$ equals each consumer's subjective discount rate ρ. We show in the next section that $r(t)=\rho$ in the steady-state equilibrium. Thus, this condition states that the appropriately discounted labor costs of developing a new product rise as firms try to speed up the process by devoting more resources to R&D. Equation (5) will hold if the $h(\cdot)$ function is downward sloping but sufficiently flat. Fifth, we make a technical restriction

$$\text{(6)}\qquad -h'(0)<\frac{(1-e^{-\rho T})h(\bar{L}^{\mathrm{N}})}{\bar{L}^{\mathrm{N}}(e^{\rho h(\bar{L}^{\mathrm{N}})}-1)T}$$

which will also hold if the $h(\cdot)$ function is sufficiently flat. As shown in Appendix A, condition (6) is sufficient but hardly necessary for the steady-state equilibrium to be unique.

Finally, we assume that the labor force in the North ($\bar{L}^{\mathrm{N}}$) is sufficiently large relative to the labor force in the South ($\bar{L}^{\mathrm{S}}$) so that

$$\text{(7)}\qquad \frac{n\alpha\bar{L}^{\mathrm{N}}}{\bar{L}^{\mathrm{S}}+\alpha\bar{L}^{\mathrm{N}}}>\frac{T}{\bar{h}}.$$

As will become clear in Section II, inequality (7) guarantees that, in any steady-state equilibrium, aggregate R&D expenditures are strictly positive.

II. The Steady-State Equilibrium

In this section, we show that a unique steady-state equilibrium exists for the dynamic, general equilibrium model of North–South trade. In this steady state, the number of dominant firms m, the relative wage of Northern workers w, the profit flow of each dominant firm π^d, the aggregate labor devoted to research and development L^R, world expenditure E^W, world wage income I^W, Northern assets A^N, and the market interest rate r are all positive constants over time and are interrelated in several specific ways.[8]

World expenditure E^W, Northern assets A^N, and the equilibrium interest rate r must be consistent with the consumer's savings–consumption decisions over time. Let t_0 represent the beginning of an R&D race where J innovations have already occurred. The representative consumer's discounted future utility from expenditure path $E(t)$, $t \in [t_0, \infty)$ is

$$(8)\quad U = \sum_{i=0}^{\infty} \int_{t_0 + i\hat{t}}^{t_0 + (i+1)\hat{t}} e^{-\rho t} \log\left[\frac{\alpha^i E(t)^n}{n^n \alpha^m}\right] dt + \Gamma(J, t_0)$$

where $\hat{t} = h(L^R)$ is the length of each steady-state R&D race and m is the number of products produced by dominant firms. Because the m products produced by dominant firms are sold at price $p^d = \alpha$ and the $n - m$ competitively produced goods are sold at price $p^c = 1$, every time an innovation occurs, the consumer's instantaneous utility increases by factor α. From the point of view of future decision making $\Gamma(J, t_0) = \int_0^{t_0} e^{-\rho t} \log u(\cdot)\, dt$ is a constant. Appendix B shows that optimal consumer behavior is characterized by a constant expenditure path over time when the steady-state interest rate equals ρ, the consumer's subjective discount rate. Furthermore, it is shown in Appendix B that the relationship among steady-state expenditure E^W, assets A^N and wage income I^W is

$$(9)\qquad E^W = \rho A^N + I^W.$$

Each consumer spends his wage income and interest earnings from his assets at each instant in time. These assets have been accumulated before the economy reaches the steady-state equilibrium. In other words, equation (9) is just a breakdown of steady-state expenditure by income source.

It is perhaps surprising that, although the instantaneous utility function is characterized by periodic jumps (caused by innovations), there nevertheless exists a steady state with constant expenditures and a constant interest rate over time. However, the optimal expenditure path is derived from the *marginal* utility of expenditure function (see Appendix B), which is invariant with respect to jumps caused by innovations.

Wage income in the world consists of income from production work and income from R&D work:

$$(10)\qquad I^W = w\bar{L}^N + \bar{L}^S.$$

Notice that equation (10) implies that R&D workers are paid concurrently. Because goods are nonstorable, world GNP must equal world expenditure E^W:

$$(11)\quad E^W = m\pi^d + w(\bar{L}^N - L^R) + \bar{L}^S.$$

The first two terms represent the value of Northern production, and the last term equals the value of Southern production.

Expected discounted profits of firm i in a typical R&D race are

$$(12)\quad -wL_i^R\left[1 - e^{-\rho h(L^R)}\right] + \frac{L_i^R}{L^R}\pi^d e^{-\rho h(L^R)}\left[1 - e^{-\rho T}\right].$$

Firm i must pay each of L_i^R workers the wage w for the duration $h(L^R)$ of the R&D race. With probability L_i^R / L^R the ith firm wins the race and earns profits π^d until its patent expires. Perfect competition and free entry in each R&D race drives expected discounted profits of each firm to zero. Summing over all firms in the R&D race, we obtain

$$(13)\quad -wL^R\left[1 - e^{-\rho h(L^R)}\right] + \pi^d e^{-\rho h(L^R)}\left[1 - e^{-\rho T}\right] = 0.$$

[8]World assets equal Northern assets and Southern expenditure equals Southern income, because Southern consumers do not participate in the capital market.

In other words, aggregate profits discounted to the beginning of an R&D race are equal to zero.

Using equations (10), (11), and (13), it can be shown that the value of aggregate assets is

$$(14)\qquad A^{\mathrm{N}} = \frac{m\pi^{\mathrm{d}} - wL^{\mathrm{R}}}{\rho} = \frac{\pi^{\mathrm{d}}}{\rho}\sum_{j=1}^{m}\left(1 - e^{-\rho j\hat{t}}\right).$$

Equation (14) implies that $A^{\mathrm{N}} > 0$. Assets must be positive in the steady state, because Northern consumers saved in the past to finance the innovation process that led to m dominant firms.

We use geometric techniques to derive the solution and perform comparative steady-state analysis. Combining equations (4), (11), and (13) yields

$$(15)\quad m = Z(L^{\mathrm{R}}, w) \equiv \frac{n\alpha}{\alpha - w} - \frac{\left[w(\bar{L}^{\mathrm{N}} - L^{\mathrm{R}}) + \bar{L}^{\mathrm{S}}\right](1 - e^{-\rho T})}{wL^{\mathrm{R}}(e^{\rho h(L^{\mathrm{R}})} - 1)}.$$

With w fixed, Z can be interpreted as the steady-state zero-profit condition expressed in (m, L^{R}) space. Given the assumptions about $h(\cdot)$ in Section I, the partial derivatives are unambiguously signed: $\partial Z/\partial L^{\mathrm{R}} > 0$, $\partial Z/\partial w > 0$, and $\lim_{L\to 0} Z(L,w) = -\infty$ for any $w \geq 1$.

The function $m = Z(L^{\mathrm{R}}, w)$ increases in L^{R} for the following reason: from condition (5), when L^{R} increases, the discounted cost of developing an innovation $L^{\mathrm{R}}(e^{\rho h(L^{\mathrm{R}})} - 1)$ increases. Equation (13) implies that to maintain zero discounted profits, dominant firm profits π^{d}, which represent the reward for winning an R&D race, must be higher. For a given wage w, π^{d} is higher only if world expenditure E^{W} is higher [eq. (4)], and from equation (11), there must be more dominant firms for world expenditure to be higher. In other words, firms can only afford to devote more resources to R&D if there are more dominant firms earning positive economic profits and, thus, higher world income and expenditure.

For a given L^{R}, an increase in w leads to a proportionate increase in π^{d} by equation (13). From equation (4), world expenditure must increase more than proportionately. Since world wage income $w(\bar{L}^{\mathrm{N}} - L^{\mathrm{R}}) + \bar{L}^{\mathrm{S}}$ increases less than proportionately with an increase in w, equation (11) implies that m must increase. Thus, for a given L^{R}, $m = Z(L^{\mathrm{R}}, w)$ increases in w. In other words, for firms to justify paying their R&D workers higher wages, world expenditure on their products must increase, and this can only occur if there are more dominant firms earning profits.

To maintain m dominant firms in the steady state, each time a patent expires, a new product must be discovered. Thus, during the period of time T, m new products must be discovered. This generates the steady-state R&D supply function in (m, L^{R}) space:

$$(16)\qquad m = R(L^{\mathrm{R}}) \equiv T/h(L^{\mathrm{R}}).$$

Given the properties of $h(\cdot)$, the R&D supply increases in L^{R}; $\partial R/\partial L^{\mathrm{R}} > 0$ and $R(0) = T/\bar{h} > 0$, because some product innovation occurs even if no resources are devoted to R&D. Finally, $R(\bar{L}^{\mathrm{N}}) = T/h(\bar{L}^{\mathrm{N}}) < n$, which guarantees that the number of dominant firms is less than the number of product groups.

The relative wage w is determined by competitive market forces. Depending on the distribution of labor endowments between the North and South, the steady-state relative wage w can exceed or be equal to one. The relative wage w cannot be less than one, since Northern workers are as productive as Southern workers and only Northern workers can do R&D-type work.

If $w > 1$ in the steady-state equilibrium, then m products are produced exclusively in the North by dominant firms and $n - m$ products are produced exclusively in the South by competitive firms, with one product from each product group being produced at any point in time. By symmetry, for each product that the South produces, the aggregate output is $\bar{L}^{\mathrm{S}}/(n - m)$, and the equilibrium price is one. Since this production must satisfy world demand, $\bar{L}^S/(n-m) = E^W/n$. Thus,

$$L^R + \frac{m\bar{L}^S}{\alpha(n-m)} = \bar{L}^N \tag{17}$$

whenever $w > 1$. Equation (17) states that all workers in the North are either engaged in R&D or manufacturing for dominant firms. It implicitly defines $m = F(L^R)$. F can be interpreted as the steady-state labor market constraint in (m, L^R) space. Clearly $\partial F/\partial L^R < 0$. Given equation (17), any increase in L^R must be matched by an equal decrease in the aggregate output of dominant firms. This can only happen if both world expenditure and the number of dominant firms decrease. When $w > 1$ in the steady-state equilibrium, the three graphs $Z(\cdot)$, $R(\cdot)$, and $F(\cdot)$ must simultaneously intersect. This case is illustrated by point A in Figure 1.

On the other hand, if a competitive product is produced in the North, it must be that Northern and Southern production workers get paid the same wage $w = 1$; that is, $L^R + mE^W/n\alpha \leq \bar{L}^N$. Then, the aggregate output for the typical Southern-produced product is $\bar{L}^S(n-m)$. However, this production does not have to satisfy demand; that is, $\bar{L}^S/(n-m) \leq E^W/n$. Thus, when $w = 1$, the graphs $Z(\cdot)$ and $R(\cdot)$ must intersect at a point where the labor market constraint $m \leq F(L^R)$ is satisfied. This case is illustrated by point B in Figure 2. It is proved in Appendix A that a unique steady-state equilibrium exists in both cases.

In this steady-state equilibrium, each product $j \in N$ experiences a Vernon-type product life cycle. Once discovered, each product is produced in the North by a dominant firm for a period of length T. Then production shifts to a competitive industry in the South (if $w > 1$). Eventually each product becomes obsolete, and world production ceases.

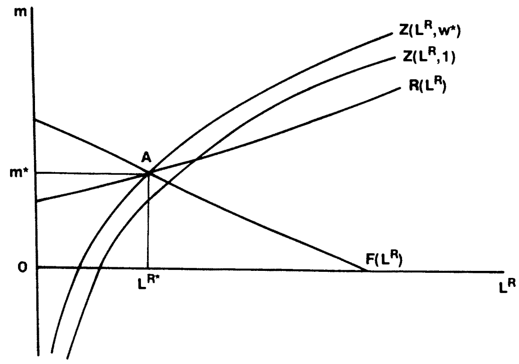

FIGURE 1. THE STEADY-STATE EQUILIBRIUM WITH $w > 1$

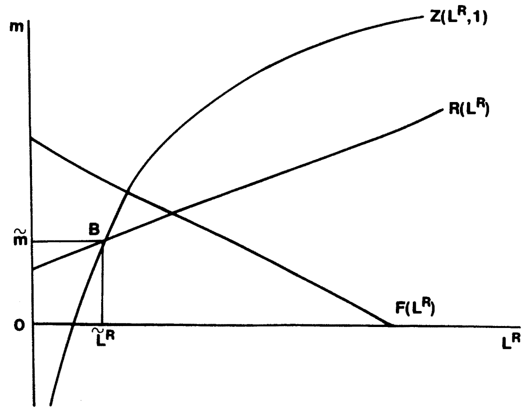

FIGURE 2. THE STEADY-STATE EQUILIBRIUM WITH $w = 1$

III. Labor Endowments and Wages in the Steady-State Equilibrium

In this section, we examine the relationship between relative labor endowments and steady-state relative wages. By varying the Southern labor force $\bar{L}^S$, we show that if $\bar{L}^S$ is sufficiently small the steady-state relative wage w equals one and that if $\bar{L}^S$ is above some critical value the steady-state relative wage w exceeds one. Furthermore, the comparative steady-state effects of an increase in the Southern labor endowment depend critically on which case we are in. To see this, consider the steady-state effect of a once-and-for-all increase in the Southern labor force $\bar{L}^S$. Increasing $\bar{L}^S$ causes both the zero profit condition $Z(L^R, 1)$ and the labor market constraint $F(L^R)$ to shift down. If the steady-state relative wage w^* equals one [and eq. (17) holds with strict inequality], then an increase in $\bar{L}^S$ increases the steady-state labor force engaged in R&D (L^R) and increases the steady-state number

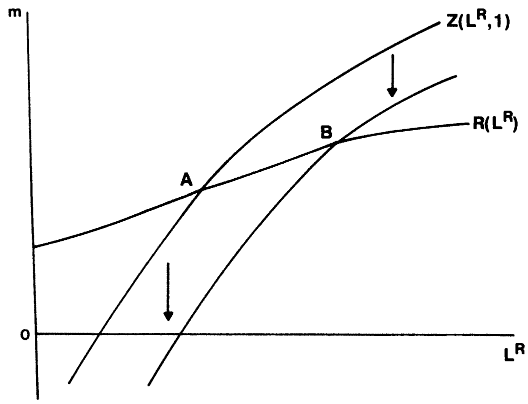

FIGURE 3. EFFECTS OF INCREASE IN SOUTHERN LABOR ENDOWMENT WHEN $w = 1$

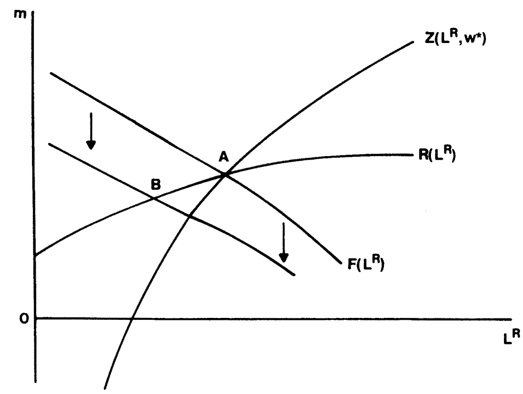

FIGURE 4. EFFECTS OF INCREASE IN SOUTHERN LABOR ENDOWMENT WHEN $w > 1$

of dominant firms in the North (m). This is illustrated by the movement from point A to point B in Figure 3. However, for sufficiently large $\bar{L}^S$, the labor market constraint becomes binding, and the steady-state relative wage begins to rise. With $w^* > 1$, an increase in $\bar{L}^S$ decreases the steady-state labor force engaged in R&D, decreases the steady-state number of dominant firms in the North, and increases the relative wage of Northern workers.[9] This case is illustrated by the movement from point A to point B in Figure 4.

The intuition behind this set of results is easy to explain. When the steady-state relative wage w^* equals one and equation (17) holds with strict inequality, at each point in time t, some Northern workers produce competitive products that are also produced in the South. An increase in the Southern labor force $\bar{L}^S$ increases Southern income I^S and Southern expenditure and thus increases world expenditure E^W. As a result of the increase in world expenditure, dominant firms want to produce more ($q^d = E^W/n\alpha$) and to hire more production workers. Since dominant-firm profits [$\pi^d = (\alpha - w)E^W/\alpha n$] increase, perfect competition in each R&D race induces firms to devote more labor L^R to R&D. With a fixed endowment of labor $\bar{L}^N$ in the North, the increased employment of production workers by dominant firms and the increased employment of R&D labor are exactly balanced by a decreased employment of production workers by competitive firms in the North. However, when the steady-state relative wage w^* exceeds one, this reallocation of labor within the North in response to an increase in $\bar{L}^S$ is not possible, because there are no workers in the North producing competitive goods. Without any change in w^*, an increase in $\bar{L}^S$ leads to excess demand for labor by firms in the North. It is still true that an increase in the Southern labor force $\bar{L}^S$ increases world expenditure E^W, and as a result, dominant firms want to hire more production workers ($q^d = E^W/n\alpha$). Thus, the relative wage w^* must rise enough [and dominant-firm profits $\pi^d = (\alpha - w)E^W/n\alpha$ fall enough] so that firms in the North hire fewer R&D workers; when firms hire fewer R&D workers, this leads to a new steady-state equilibrium with fewer dominant firms.

IV. The Effects of Patents and Tariffs

First, consider the steady-state effect of a once-and-for-all increase in the patent length T (or a decrease in the rate of technology transfer to the South). Increasing T causes the zero profit condition $Z(L^R, 1)$ to shift down and causes the R&D supply function $R(L^R)$ to shift up but leads to no

[9]An increase in $\bar{L}^S$, given w, shifts down $Z(\cdot)$ (not shown in Fig. 4). Since the final equilibrium is at point B, w and $Z(\cdot)$ must appropriately shift up.

change in the labor market constraint $F(L^R)$. If the steady-state relative wage w^* equals one [and eq. (17) holds with strict inequality], then an increase in T *increases* both the steady-state labor force engaged in R&D and the steady-state number of dominant firms in the North. This case is illustrated in Figure 5. Increasing T increases the reward for innovative activity. Firms respond to this incentive by increasing the resources they devote to R&D. However, if the steady-state relative wage w^* exceeds one, then an increase in T *decreases* the steady-state labor force engaged in R&D, *increases* the steady-state number of dominant firms in the North, and *increases* the relative wage of Northern workers. This is illustrated in Figure 6. This counterintuitive result is explained as follows: increasing T increases the demand for production workers by dominant firms in the North, because dominant firms have longer lives. Since $\bar{L}^N$ is fixed, the increased employment of production workers in the North must be exactly balanced by a decreased employment of R&D workers. The relative wage w^* must rise enough and dominant-firm profits π^d fall enough so that profit-maximizing firms in the North appropriately reduce their R&D expenditures.

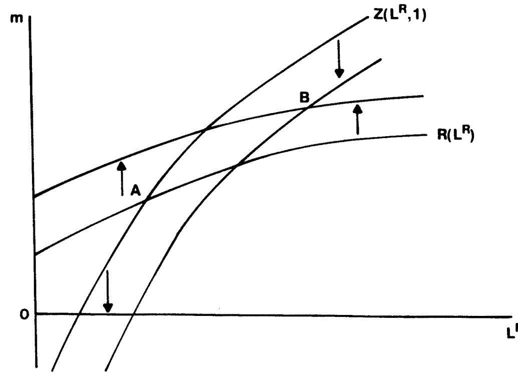

FIGURE 5. EFFECTS OF INCREASE IN PATENT LENGTH WHEN $w = 1$

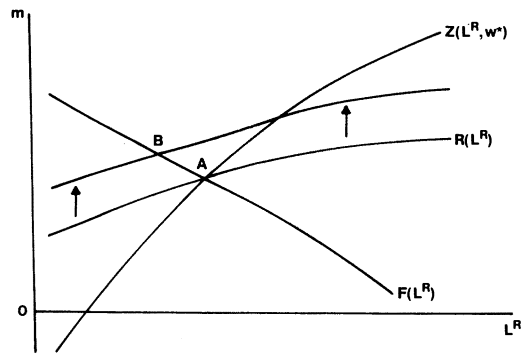

FIGURE 6. EFFECTS OF INCREASE IN PATENT LENGTH WHEN $w > 1$

Because each product experiences a Vernon-type product life cycle in the steady-state equilibrium, the international trade pattern repeatedly changes over time. Industries in the North die in the sense that production of particular products ceases. Other industries in the North are born when new products are discovered. Thus, in this steady-state equilibrium, production workers in the North repeatedly lose their jobs and must find employment in other sectors of the economy. Given this scenario, tariffs designed to save the jobs of production workers in dying industries would have considerable political support.

We now relax the previous assumption that free trade prevails between the North and the South throughout time and explore the comparative steady-state effects of tariffs designed to protect dying industries in the North from Southern competition. We will assume that the labor force $\bar{L}^N$ in the North is sufficiently small so that the steady-state relative wage of Northern production workers w^* exceeds one. This assumption is supported by empirical evidence.[10] At each time t, the government in the North imposes per-unit tariffs on the importation of the $\hat{m}$ products whose patents have most recently expired. The government chooses $\hat{m}$ as its policy instrument; that is, it chooses how many industries in the North to protect from Southern competition. For these tariffs to have any

[10]Keith Maskus (1989) and Christopher Clague (1988) present evidence showing that the wage of unskilled workers in some LDC's is about one-tenth that of unskilled Northern workers.

effects on employment in the $\hat{m}$ Northern industries, each per-unit tariff must be at least $w^* - 1$. In other words, each tariff must be prohibitive. We will assume that this holds for each protected industry. As a result, there is no international trade in any of these $\hat{m}$ protected products, and no government revenue is generated by the tariffs.

In the steady-state equilibrium with $\hat{m}$ products protected, m products are produced exclusively in the North by dominant firms, $\hat{m}$ products are produced both in the North and in the South, and $n - m - \hat{m}$ products are produced exclusively in the South by competitive firms. Since Southern income I^S still equals $\bar{L}^S$ in equilibrium, the South must produce $\bar{L}^S/n$ units of each of the $\hat{m}$ protected products for domestic consumption. Since Southern production must satisfy world demand for each of the $n - m - \hat{m}$ products, by symmetry,

$$\frac{E^W}{n} = \frac{\bar{L}^S - \hat{m}\left(\frac{\bar{L}^S}{n}\right)}{n - m - \hat{m}} \tag{18}$$

must be satisfied. The right-hand side of equation (18) represents how much Southern labor must be used to produce each of the $n - m - \hat{m}$ products that are produced exclusively in the South.

Steady-state equations (15) and (16) remain unchanged by the introduction of tariffs. Given that $w > 1$, equation (17) becomes

$$L^R + \frac{mE^W}{n\alpha} + \frac{\hat{m}E^N}{nw} = \bar{L}^N. \tag{19}$$

Using the identity $E^W = E^N + I^S$ and substituting equation (18) into (19) we get

$$L^R + \left[\frac{m}{\alpha} + \frac{\hat{m}}{w}\right]\frac{\bar{L}^S\left(1 - \frac{\hat{m}}{n}\right)}{n - m - \hat{m}} - \frac{\hat{m}}{n}\frac{\bar{L}^S}{w} = \bar{L}^N. \tag{20}$$

This equation implicitly defines the new $m \equiv F(L^R, \hat{m}, w)$ function. It is easily verified that $\partial F/\partial L^R < 0$, $\partial F/\partial \hat{m} < 0$, and $\partial F/\partial w > 0$. Furthermore, when $\hat{m} = 0$, the new $F(\cdot)$ function coincides with the old $F(\cdot)$ function.

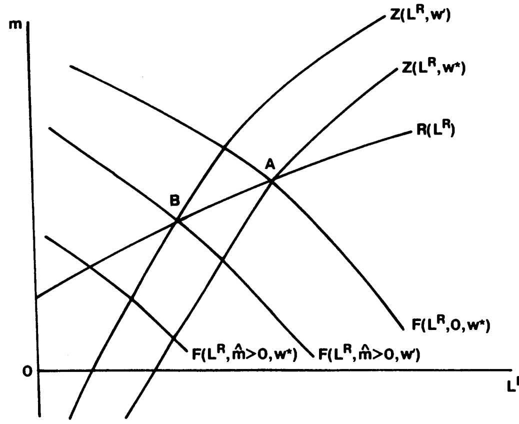

FIGURE 7. EFFECTS OF INCREASE IN THE NUMBER OF PROTECTED INDUSTRIES WHEN $w > 1$

Suppose that in the initial steady-state equilibrium $\hat{m} = 0$ and $w = w^* > 1$. This is illustrated by the intersection of the $m = Z(L^R, w)$, $m = R(L^R)$, and $m = F(L^R, \hat{m}, w)$ functions at point A in Figure 7. An increase in $\hat{m}$ shifts down the labor market constraint $F(\cdot)$. Now there is an excess demand for Northern labor at point A. The steady-state relative wage w must rise above w^*, shifting up both the zero profit condition $Z(\cdot)$ and $F(\cdot)$ until a new intersection is established (at point B, with $w = w' > w^*$).

Thus, we can conclude that when Northern production workers earn higher wages than their Southern counterparts, an increase in the number of protected industries in the North ($\hat{m}$) *decreases* the steady-state rate of product innovation in the North, *decreases* the steady-state number of dominant firms in the North, and *increases* the steady-state relative wage of Northern production workers.

The intuition behind this result is easy to explain. An increase in the number of protected industries in the North raises the demand for Northern production workers. With the Northern labor endowment fixed, the labor devoted to R&D must decline. This necessitates an increase in Northern relative wages, which raises production costs for dominant firms and lowers dominant-firm profit flows. As a result, R&D becomes less profitable, and the steady-state number of dominant firms (winners of R&D races) declines. Notice that in the case of $w=1$, increasing the number of protected industries in the North does not have any effect on the steady-state number of dominant firms and the rate of product innovation.

The introduction of a nontraded sector in the North does not affect the impact of protectionism on the rate of product innovation. The effects of patents on the rate of innovation are robust to the introduction of a nontraded good but may not be robust to the introduction of many nontraded goods. If a sufficiently large fraction of the economy involves nontraded goods, then an increase in T could lead to an increase in L^{R} when $w>1$.[11]

V. Conclusion

We have analyzed a dynamic model of innovation, technology transfer, and international trade. Although highly stylized and in some respects unrealistic, this model nevertheless captures some of the forces that are shaping the pattern of trade in the real world today—forces that are not easily captured in the traditional Heckscher-Ohlin trade model.

In our model, sustained product innovation in the North enables Northern workers to earn higher wages than comparable workers in the South. We have carefully analyzed how the rate of product innovation and the relative wage of Northern workers are affected not only by changes in the rate of technology transfer and the world labor endowment, but also by protectionist government policies. What results is an explanation for the small number of new industries in the North that have arisen to replace older, dying industries as employers of Northern labor. By artificially inflating the wages of Northern workers, protectionist government policies induce sluggish innovative performance in the North.

By focusing on the steady-state equilibrium, we have necessarily abstracted from examining the welfare implications of comparative steady-state exercises. This important task constitutes a nontrivial extension of our model, and it represents a topic for future research.

[11]An appendix containing an algebraic analysis of the effects of patents and tariffs in the presence of nontraded goods is available from the first author upon request.

APPENDIX A

Existence and Uniqueness of Steady-State Equilibrium

Proving that a steady-state equilibrium exists reduces to showing that either (i) $m=Z(L^{\mathrm{R}},w)$, $m=R(L^{\mathrm{R}})$, and $m=F(L^{\mathrm{R}})$ simultaneously intersect at some point $(\hat{L}^{\mathrm{R}},\hat{m},\hat{w})\in R_{+}^{3}$ for some $\hat{w}>1$ or (ii) $m=Z(L^{\mathrm{R}},1)$ and $m=R(L^{\mathrm{R}})$ intersect at some point $(\tilde{L}^{\mathrm{R}},\tilde{m})\in R_{+}^{2}$ where $\tilde{m}\leq F(\tilde{L}^{\mathrm{R}})$. The graph of $R(\cdot)$ is upward sloping in L^{R}, and the graph of $F(\cdot)$ is downward sloping in L^{R}. Moreover, $R(0)<F(0)$ and $R(\bar{L}^{\mathrm{N}})>F(\bar{L}^{\mathrm{N}})=0$ [given the properties of the $h(\cdot)$ function]. Consequently the functions $R(\cdot)$ and $F(\cdot)$ must have a unique intersection, which we will denote $(L^{\mathrm{R}*},m^{*})$. (See Fig. 1).

Suppose that the intersection of $R(\cdot)$ and $F(\cdot)$ lies above the $Z(\cdot)$ graph evaluated at $w=1[Z(L^{\mathrm{R}*},1)<m^{*}]$. Then, increasing the wage shifts the $Z(\cdot)$ graph upward, and since $\lim_{w\to\alpha}Z(L^{\mathrm{R}*},w)=+\infty$, there exists a wage $w^{*}>1$ such that all three graphs intersect simultaneously at $(L^{\mathrm{R}*},m^{*},w^{*})$. This intersection is unique, corresponds to the case-(i) steady-state equilibrium, and is illustrated by point A in Figure 1.

Suppose that the intersection of $R(\cdot)$ and $F(\cdot)$ does not lie above the $Z(\cdot)$ graph evaluated at $w=1[Z(L^{\mathrm{R}*},1)\geq R(L^{\mathrm{R}*})=m^{*}]$. Notice that $R(0)-Z(0,1)>0$ and that $R(L^{\mathrm{R}*})-Z(L^{\mathrm{R}*},1)\leq 0$ [$\lim_{L^{\mathrm{R}}\to 0}Z(L^{\mathrm{R}},1)=-\infty<0<R(0)=T/\bar{h}$]. This guarantees that the $Z(\cdot)$ function evaluated at $w=1$ and the $R(\cdot)$ function must intersect for

some $\tilde{L}^{R}$ and $\tilde{m}$ which are less than or equal to L^{R*} and m^*, respectively. Consequently $w=1$, $\tilde{L}^{R}$ and $\tilde{m}$ are steady-state equilibrium values satisfying case (ii). This steady-state equilibrium is illustrated by point B in Figure 2.

The steady-state equilibrium is unique provided that the functions $Z(L^{R},1)$ and $R(L^{R})$ have at most one intersection in the interval $(0,\bar{L}^{N}]$. It suffices to show that

$$\text{(A1)}\quad \frac{\partial Z(L,1)}{\partial L} = [(\bar{L}-L)(1-e^{-\rho T})Lh'(L)\rho e^{\rho h(L)} + \bar{L}(1-e^{-\rho T})(e^{\rho h(L)}-1)] \times \left[L^2(e^{\rho h(L)}-1)^2\right]^{-1} > \frac{\partial R(L)}{\partial L} = \frac{-Th'(L)}{[h(L)]^2}$$

for all $L \in (0,\bar{L}^{N})$. From equation (5), it follows that

$$\text{(A2)}\quad 0 > e^{\rho h(L)}\rho L h'(L) > 1 - e^{\rho h(L)}.$$

Substituting (A2) into (A1), it suffices to show that

$$\text{(A3)}\quad \frac{1-e^{\rho T}}{L(e^{\rho h(L)}-1)} > \frac{-Th'(L)}{[h(L)]^2}$$

for all $L \in (0,\bar{L}^{N})$. Since $h''(L) \geq 0$ and $h'(L) < 0$ for all $L \in (0,\bar{L}^{N})$,

$$\text{(A4)}\quad \frac{-Th'(L)}{[h(L)]^2} \leq \frac{-Th'(0)}{[h(\bar{L}^{N})]^2}.$$

Also, by equation (5)

$$\text{(A5)}\quad \frac{1-e^{-\rho T}}{L(e^{\rho h(L)}-1)} \geq \frac{1-e^{-\rho T}}{\bar{L}^{N}(e^{\rho h(\bar{L}^{N})}-1)}$$

for all $L \in (0,\bar{L}^{N})$. Combining equations (A3), (A4), and (A5) yields equation (6). Thus, the steady-state equilibrium is unique.

APPENDIX B

Steady-State Consumer Behavior

With time-separable utility, the representative Northern consumer's maximization problem can be solved in two stages.[12] First, for given total expenditure at time t, $E(t)$, and prices of available products, we find the allocation of expenditure that maximizes the consumer's CDP utility function. Then we solve for the time path of expenditures that maximizes U.

The first stage of the consumer optimization problem was analyzed in detail in Section II. The second stage involves choosing the optimum expenditure path $E(t)$, $t \in (0,\infty)$. The representative Northern consumer's assets $A(t)$ evolve according to the equation[13]

$$\text{(B1)}\quad \dot{A}(t) = r(t)A(t) + I(t) - E(t)$$

where $r(t)$ is the instantaneous interest rate and $I(t)$ is the consumer's income at time t. Dots denote time derivatives. Furthermore, assets and income must satisfy the feasibility condition

$$\text{(B2)}\quad \lim_{t\to\infty} \inf\left[A(t) + \int_t^{\infty} \exp\left(-\int_t^{\tau} r(x)\,dx\right) \times I(\tau)\,d\tau\right] \geq 0.$$

This feasibility condition states that the sum of assets and the discounted value of income is nonnegative in the limit as t approaches infinity.

Infinitely lived consumers maximize total lifetime utility [eq. (1)] subject to equations (B1) and (B2). After some algebraic manipulation, equation (8), which is the lifetime

[12]See Hal Varian (1984 p. 148).

[13]See Kenneth Arrow and Mordecai Kurz (1970 Ch. 7).

utility function, reduces to

$$\text{(B3)}\quad U = n\int_{t_0}^{\infty} e^{-\rho t}\log E(t)\,dt + \left(\frac{e^{-\rho t_0}}{\rho}\right)\log\frac{1}{n^n\alpha^m} + (\log\alpha)\left(\frac{e^{-\rho t_0}}{\rho}\right)\left(\frac{e^{-\rho\hat{t}}}{(1-e^{-\rho\hat{t}})}\right) + \Gamma(J,t_0).$$

Notice that the second, third, and fourth terms are all constants from the point of view of the consumer [who is choosing $E(t)$]. The third term represents the discounted value of all future innovations in the steady state. If $\alpha = 1$, then new products are identical to old products, and this term disappears.

We conjecture that, in the steady state, the market interest rate $r(t)$ is constant over time and equal to the consumer's discount parameter ρ. We will subsequently verify that, given $r = \rho$, the optimum path of consumer expenditures and assets will also be constant over time in the steady state. Furthermore all markets will clear at each instant in time.[14]

Consequently, the consumer solves the following optimal control problem in the steady state at time t_0:

$$\text{(B4)}\quad \max_{E(t)\geq 0;\, t\in[t_0,\infty)} n\int_{t_0}^{\infty} e^{-\rho t}\log E(t)\,dt + \text{constant}$$

subject to $A(t_0) = A_0$,

$$\text{(B5)}\quad \dot{A}(t) = \rho A(t) + I - E(t)$$

and

$$\text{(B6)}\quad \lim_{t\to\infty}\inf\left[A(t)+\frac{I}{\rho}\right]\geq 0.$$

The constraints (B5) and (B6) follow from (B1) and (B2), assuming that $r(t) = \rho$ for all $t \geq t_0$.

The current-value Hamiltonian for this optimal-control problem is

$$\text{(B7)}\quad H = \log E(t) + \lambda(t)\{\rho A(t) + I - E(t)\}$$

and the necessary conditions are $1/E(t) = \lambda(t)$, $\dot{\lambda}(t)/\lambda(t) = 0$, and equations (B5) and (B6). Thus,

$$\text{(B8)}\quad E(t) = E_0.$$

Solving (B5), we get

$$\text{(B9)}\quad A(t) = e^{\rho t}\left\{A_0 + \frac{I-E_0}{\rho}\right\}\frac{E_0 - I}{\rho}.$$

If $A_0 + (I - E_0)/\rho < 0$, then the dominant term in (B9) approaches $-\infty$ as t approaches $+\infty$, and the feasibility condition (B6) is not satisfied. If $A_0 + (I - E_0)/\rho > 0$, then the dominant term approaches $+\infty$, and (B6) is clearly satisfied. However, (B6) would still be satisfied if E_0 were increased slightly. Hence higher consumption at every instant in time would be feasible, and therefore the expenditure path $E(t) = E_0$ would not be optimal. Thus, the optimal expenditure path must satisfy

$$\text{(B10)}\quad A_0 + \frac{I-E_0}{\rho} = 0$$

and therefore

$$\text{(B11)}\quad A(t) = A_0 \equiv \frac{E_0 - I}{\rho}$$

which obviously satisfies (B6).

To summarize, we have shown that, if the steady-state interest rate $r(t) = \rho$, then the consumer optimizes by choosing a constant expenditure path over time E_0 where

$$\text{(B12)}\quad E_0 = \rho A_0 + I.$$

[14]Alternatively, one could use (6) and (7), allowing the instantaneous interest rate $r(t)$ to vary over time. In this case, if one assumes that expenditure does not change at the steady state, then $r(t) = \rho$; that is, the interest rate is constant in the steady state. For more details, see Grossman and Helpman (1989), in particular their equation 5.

That is, the consumer spends his wage income and interest earning on his assets, at each instant in time.

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