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HIGH-TECHNOLOGY-INDUSTRY TRADE AND INVESTMENT: THE ROLE OF FACTOR ENDOWMENTS

by

Elias Dinopoulos, James F. Oehmke and Paul S. Segerstrom*

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DEC 3 1992

October 1989
Revised September 1990

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*We would like to thank Jim Anderson, Jagdish Bhagwati, Leonard Cheng, Robert Feenstra, Gene Grossman, Carsten Kowalczyk, David Sappington, Costas Syropoulos and participants in workshops at the University of Chicago, University of Florida, the Pennsylvania State University and the Midwest International Economics meetings at Washington University for useful comments and suggestions. Any remaining errors are the sole responsibility of the authors.

HIGH-TECHNOLOGY-INDUSTRY TRADE AND INVESTMENT: THE ROLE OF FACTOR ENDOWMENTS.

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Abstract

This paper develops a dynamic general equilibrium model of international research and development (R&D) competition based on the Heckscher-Ohlin structure of production. We analyze the model's unique steady-state equilibrium in which both R&D expenditures and the rate at which firms discover new superior products are constant over time. The model generates intrasectoral trade, intersectoral trade, product cycles and multinational corporations even when factor price equalization prevails across countries. The extent of these phenomena depends on factor endowments. Finally, in the absence of R&D incentives the model reduces to the familiar Heckscher-Ohlin model.

Keywords: R&D, factor endowments, high-technology-industry, multinationals, product innovation.

JEL Classification: 411

I: Introduction

We live in a world characterized by rapid technological change. The lure of monopoly profits drives firms to enter into research and development (R&D) races to discover new superior quality products. When a new, superior-quality product is discovered it replaces lower-quality products both in the country of discovery and in that country's trading partners. The pattern of trade in high-technology goods is thus inextricably linked to the pattern of R&D and product improvement. The first paper to study sequences of innovative R&D races in a dynamic general equilibrium context, Segerstrom, Anant and Dinopoulos (1987), used a simple one factor Ricardian production structure to analyze North-South trade by assuming that only firms in the North could engage in R&D. The present paper explores the implications of R&D competition for international trade between advanced countries when both countries can engage in R&D. We present a dynamic general equilibrium model of R&D competition which substantially generalizes the analysis in Segerstrom, et. al. (1987) by allowing firms in both countries (home and foreign) to engage in R&D and by using a two factor Heckscher-Ohlin production structure in each sector of the world economy.

In our model, all consumers maximize their discounted utility, all firms maximize their expected discounted profits and all markets clear throughout time. Firms can engage in a sequence of R&D races, with the winner of each R&D race discovering how to produce a new superior quality product. Successful innovators earn dominant firm profits for a finite period of time (the patent length T) before they are copied by a competitive fringe of initiating firms.

We show that this model has a unique steady state equilibrium in which R&D expenditures and the rate of product innovation are positive and constant over time. We analyze the pattern of international trade and investment in this steady state using the concept of an integrated world equilibrium, which was developed by Dixit and Norman (1980) and Helpman and Krugman (1985).

Four interesting features emerge from our analysis: 1) Different factor endowments across countries can explain why some products must experience product cycles (products initially discovered by home country firms must eventually be produced and exported by the foreign country), even when factor price equalization prevails. Previous work on product cycles (e.g., Segerstrom et. al (1987), Grossman and Helpman (1989), Krugman (1979)) required cost differences across countries. 2) Different factor endowments across countries can also explain why some products must be produced by multinational corporations (discovered by a home country and produced in the foreign country by the same firm) even when factor price equalization prevails. 3) A country which is labor abundant relative to the aggregate asset-adjusted factor endowment can be a net exporter of capital intensive goods. Thus steady-state assets in our model can serve to reverse the traditional Heckscher-Ohlin relationship between relative factor abundance and the factor content of international trade. 4) Finally, our model generates intra-industry trade without any scale economies or product differentiation. Unlike other models of intra-industry trade (see Helpman and Krugman (1985, chapter 7)), in the absence of enforceable patent protection ($T=0$), our model collapses into the familiar Heckscher-Ohlin model.

This paper is closely related to Grossman and Helpman (1989), who also study R&D races and the effects of factor endowments on international trade patterns in a dynamic general equilibrium context.[1] The main difference between the two papers concerns product imitation. Grossman and Helpman assume that firms that which discover new, superior products earn dominant firm profits until there is further innovation. Since there is no product imitation, they implicitly analyze a special case of our model, namely that of perfect and infinite patent protection ($T=+\infty$). As a result product cycles do not emerge in their analysis. Grossman and

[1]See Dinopoulos et al. (1990) for a more detailed comparison.

Helpman justified the absence of imitation in their analysis by arguing that firms would have no incentive to engage in costly imitative activities in their model. However, Segerstrom (1990) has shown that the Grossman and Helpman model has a steady-state equilibrium where firms engage in costly imitative as well as costly innovative R&D activities. None of the qualitative results in the present paper would be affected if the somewhat different R&D structure in Grossman and Helpman (1989b) or in Segerstrom (1990) were used.

The rest of this paper is organized as follows: In Section II, the dynamic general equilibrium model is presented. In section III, we characterize the world integrated steady state equilibrium. International trade and investment patterns are explained in Section IV and finally, our conclusions are presented in Section V.

II. The Model

There are two countries in the world, home and foreign. The home country has aggregate endowments of labor, L, and capital, K, which do not change over time. The foreign country also has aggregate endowments of labor, L^*, and capital, K^*, which do not change over time. Let $\hat{L} \equiv L + L^*$ and $\hat{K} \equiv K + K^*$ denote the world endowments of labor and capital.

The production side of each country's economy is characterized by three sectors: outside goods (Y), high-technology industry (X) and R&D services (R). The outside-goods sector consists of all industries that do not experience product innovation. The high-technology industry sector consists of all industries with products which can be replaced by newly discovered products of higher quality. The R&D services sector supplies R&D services which in turn generate the discovery of new products in the high-technology industry sector.

Manufacturing of all products within a sector of the world economy is characterized by an identical neoclassical production function utilizing the two inputs labor and capital. Constant returns to scale prevails in each sector and production function isoquants are strictly convex.

Letting w_L and w_K denote the wage and rental rates prevailing in the world economy, we can summarize the technology of each sector using three distinct continuously differentiable unit cost functions $c_i(w_L,w_K)$, $i \in \{X,Y,R\}$. Let $c_{ij} \equiv \partial c_i/\partial w_j$, $j \in \{K,L\}$, $i \in \{X,Y,R\}$ and let $w_L=1$, so that w_K denotes the relative rental rate of capital. We will assume that $c_{KY}(w_K)/c_{LY}(w_K) < c_{KX}(w_K)/c_{LX}(w_K) < c_{KR}(w_K)/c_{LR}(w_K)$ for all $w_K>0$; that is, R&D services is the most capital intensive sector, followed by the high-technology industry and outside good sectors.

In both countries, infinitely lived consumers maximize total lifetime utility. Each consumer in the world 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. We adopt a particular form of $U(\cdot)$,

$$U(x_1,x_2,...) = \left[\prod_{j=1}^{n} \left(\sum_{i=0}^{\infty} \alpha^i x_{j+Ni} \right) \right] \left[\prod_{K=n+1}^{N} x_K \right] \tag{2}$$

This CDP (Cobb-Douglas with Perfect Substitutes) utility function was introduced in Segerstrom, et al. (1987) and the "continuum of industries" version is used in Grossman and Helpman (1989). N is the fixed number of industries in the economy. There are n high-technology industries (where product innovation can occur) and N-n outside-good industries (where no product innovation can occur). Each high-technology industry consists of a countably infinite set of products which are perfect substitutes. Product group j (j=1,2,3, . . ., n) consists of products j, N+j, 2N+j, . . . At any point in time, only a finite number of different products can be consumed as the rest of these products have not been discovered yet. New products are discovered in a sequence; product j is discovered first, then product j+1, etc., 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 only products 1, 2, . . ., N are initially available for consumption. Given time separability, consumers are, in effect, maximizing the utility function $\tilde{U} = X_1 X_2 \ldots X_N$ at that instant in time. The discovery of product N+1 means that consumers are now, in effect, maximizing the utility function $\tilde{U} = (X_1 + \alpha X_{N+1}) X_2 \ldots X_N$. If products 1 and N+1 are sold at the same price (as will be the case in our model after the patent on product N+1 expires), 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.

At any point in time, products are 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 knows how to produce. Products in the outside goods sector necessarily belong to the first set. Firms that produce products in the second set are called dominant firms.

The world economy starts at time 0. At this time, all firms in the world know how to produce products 1, 2..., N. Time 0 represents the beginning of a sequence of R&D races between firms in the world to discover the remaining products (N+1, N+2, . . ., N+n, 2N+1, 2N+2, ..., 2N+n, ...). At the beginning of the jth R&D race each firm i (independently of which country it is located in) commits to producing an amount R_{ij} of R&D services for the duration of the jth race. The winner of the R&D race becomes the only producer of the newly discovered product in both countries for a period of time $T>0$.[2] After this patent period, the new product's production technology becomes common knowledge to all firms in the world and perfect competition prevails in its production and marketing.[3] We assume that free trade prevails between the two countries and the only government intervention is perfect enforcement of the finite patent T for each innovation.

The length $\hat{t}_j$ of the jth race is a decreasing function of the aggregate R&D services devoted to the race $\hat{R}_j$, that is $\hat{t}_j = h(R_j)$ where $R_j = \sum_i R_{ij}$. We follow the notation that hats denote world variables and asterisks denote variables of the foreign country. The probability that firm i wins the jth race is given by $(R_{ij}/\hat{R}_j)$. It follows that the probability that a home-country firm wins the jth race is given by $R_j/\hat{R}_j$, and that of a foreign-country firm winning the race is $R_j^*/\hat{R}_j$, where R_j and R_j^* are aggregate R&D services devoted to the jth race by the home and foreign countries respectively $(R_j+R_j^* = \hat{R}_j)$. Consequently, the larger the fraction of R&D services devoted by a firm or a country the higher the probability that it wins the R&D race. Although the length of each R&D race is a deterministic function of world R&D services, each firm and each country face uncertainty.

We impose several restrictions on the $h(\cdot)$ function that defines the length of each R&D race. First, $h(\cdot)$ is assumed to be continuously differentiable with $h'(\cdot)<0$.. This implies that product innovation occurs at a faster rate when there are more resources devoted to R&D. Second $\bar{h} \equiv h(0) < +\infty$, that is some product innovation occurs even if no resources are devoted

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[2]The parameter T can be thought as a "patent" length or as the exogenous time lag after which technology becomes public knowledge. In the present paper we assume that T is identical in both countries. Dinopoulos, et. al. (1989) analyzed the case of country-specific patent lengths in a partial equilibrium framework.

[3]In many high-technology industries, imitation occurs rapidly. See Dick (1989) for a discussion of imitation in the computer chip industry.

to R&D. Third, for all $(\hat{R})>0$, $h(\hat{R}) > 0$ and $h''(\hat{R}) > 0$, that is innovation never occurs instantaneously. Fourth,

$$\frac{d}{d\hat{R}}\ \hat{R}\left(e^{\rho h(\hat{R})}-1\right) > 0 \tag{3}$$

Notice that $\int_{-h(\hat{R})}^{0} c_R\hat{R}e^{-\rho t}dt = c_R\hat{R}(e^{-\rho h(\hat{R})}-1)/\rho$ is the cost of developing a new product discounted to the end of the R&D race when c_R is the unit cost of R&D services and ρ is the market interest rate. Thus condition (4) states that when the market rate of interest is ρ, which will be the case in the steady state, the costs of developing a new product rise as firms try to speed up the process by devoting more resources to R&D.

We assume that there is a capital market in the world which supplies the savings of 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 finance their R&D expenditures. Each firm issues a risky security which yields a positive return if it wins and a negative return if it loses an R&D race. By holding a diversified portfolio of assets, consumers are able to completely diversify away risk. Thus free entry into each R&D race implies that firms enter each race until expected discounted profits are driven to zero.

At any time, perfect competition prevails in the markets for all products which are not produced by dominant firms. Thus, the market price of R&D services, of all goods in the outside-goods sector, and of the goods in the high-technology industry sector whose patent T has expired, equals the unit costs of the particular sector. To determine the price and instantaneous profits of a dominant firm, we impose the condition $h(R^w)n > T$ where R^w is the maximum amount of R&D services possible (obtained if all resources of the world $\hat{K}$ and $\hat{L}$ were devoted to R&D). This condition guarantees that there are never two dominant firms producing in the same product group. At time t, the dominant firm producing product j must compete only against a competitive fringe of firms producing a lower quality good j-N.

Both dominant firms and firms in the competitive fringe simultaneously set prices and we calculate the Bertrand-type Nash equilibrium. Let $\hat{E}$ represent instantaneous world expenditure. Equations (1) and (2) imply that the world expenditure allocated to products in the jth product group is $\hat{E}/N$, where N is the total number of product groups. Let p_X denote the price charged by the competitive fringe firms: p_X equals the unit costs in the high-technology-industry sector. The dominant firm has zero sales if it charges a price p^d greater than αp_X. The competitive fringe has zero sales if p^d is less than αp_X. If $p^d = \alpha p_X$ then consumers are indifferent between spending all expenditure $\hat{E}/N$ on product j and spending $\hat{E}/N$ on product j-N. We assume that all indifferent consumers buy from the dominant firm. Then dominant firm profits are

$$\Pi(p^d) = \begin{cases} 0 & \text{if } p^d > \alpha p_X \\ (p^d - p_X)\dfrac{\hat{E}}{p^d N} & \text{if } p^d \leq \alpha p_X \end{cases} \tag{4}$$

These profits are maximized where $p^d = \alpha p_X$ and maximum instantaneous profits are:

$$\Pi^d = b\hat{E}/N \tag{5}$$

where $b \equiv (\alpha-1)/\alpha > 0$. The competitive fringe constrains each dominant firm from charging a price greater than αp_X.

To complete the description of the model, we introduce some technical assumptions. Let $w_K^1>0$ denote the relative rental rate which generates the same capital:labor ratio in the R&D services sector as exists in the world, and let $w_K^2>w_K^1$ denote the relative rental rate which generates the same capital:labor ratio in the outside-goods sector as exists in the world. We assume that there exists a constant $c>0$ such that

$$0 \leq h'(\hat{R}) \leq \frac{-c(1-\frac{bT}{h(0)N})^2 + c_R(w_K^1)[1-\frac{bT}{h(R^w)N}]}{\frac{Tb}{h^2(R^w)N}[w_K^2\hat{K} + \hat{L}]} \tag{6}$$

$$\text{and for all } w_K \epsilon (w_K^1, w_K^2),\ \ c_{LR}(w_K) < c\frac{c_{LX}(w_K^1)}{Nc_X(w_K^1)}(n-bT/h(R^w)) + \frac{c_{LY}(w_K^1)(N-n)}{Nc_Y(w_K^1)]} \tag{7}$$

Equation (6) states that the $h(\hat{R})$ function must be downward sloping but sufficiently flat; that is, (6) [as well as (4)] places an upper bound on the extent to which increased R&D speeds up the pace of innovative activity. (7) states that the labor input used to produce a unit of R&D services must be sufficiently small. This restriction is consistent with our earlier assumption that the R&D services sector is the most capital intensive of the three sectors. Finally, we will assume that for all $w_K \epsilon (w_K^1, w_K^2)$,

$$d/dw_K[c_{LX}(w_K)/c_X(w_K)] \geq 0; \text{ and } d/dw_K[c_{LY}(w_K)/c_Y(w_K)] \geq 0 \tag{8}$$

Condition (8) states that labor's share of factor income in the X and Y sectors does not fall as capital becomes more expensive. This condition will hold if there are sufficiently large possibilities for substituting labor for capital in these sectors. For example, (8) will hold if the X and Y sectors have Cobb-Douglas production functions.

III: Steady State Integrated Equilibrium

In this section, we show that a unique, steady-state, integrated equilibrium exists for the dynamic, general-equilibrium model. In the steady state, the number of dominant firms in the world, $\hat{m}$, world expenditure, $\hat{E}$, and dominant firm profits, Π^d, are constant. The relative rental rate for capital, w_K, world R&D services, $\hat{R}$, and the market interest rate r are all constants over time. By an integrated equilibrium, we mean that this is the resource allocation that would be obtained in the world if goods, services and factors of production were all perfectly mobile.

In Segerstrom, et al (1987), it is shown that each consumer maximizes discounted utility by choosing a constant expenditure path over time if and only if the market interest rate r equals the subjective discount rate ρ. Since the steady-state, equilibrium interest rate must equal ρ, we are justified in restricting attention to constant expenditure paths.

Let p_X, p_Y and p_R denote the integrated-equilibrium prices that prevail in the competitive fringe of sector X, the outside-goods sector and the R&D sector, respectively. Zero-profit conditions in these goods, which are all produced competitively, require that each price equals the sector's unit costs: $p_i = c_i(w_K)$; $i \epsilon \{X, Y, R\}$.

When firm i engages in the jth R&D race, it must incur the cost $c_R R_{ij}$ for the duration $h(\hat{R}_j)$ of the race. With probability $R_{ij}/\hat{R}$ firm i wins the race and earns dominant firm profits, Π^d, until its patent expires. Free entry into each R&D race drives each firm's discounted profits to zero. Aggregating over all firms, we obtain the zero discounted profit condition for the world R&D sector

$$-c_R\hat{R}[1-e^{-\rho h(\hat{R})}] = e^{-\rho h(\hat{R})}\Pi^d(1-e^{-\rho T}) \tag{9}$$

To maintain $\hat{m}$ dominant firms in the steady state, each time a patent expires, a new product must be discovered. Thus during the period of time T, $\hat{m}$ new products must be discovered, so that

$$\hat{m} = \frac{T}{h(\hat{R})} . \tag{10}$$

Using Shephard's lemma, the full employment condition for world labor can be stated as

$$c_{LX}(n-\hat{m})\hat{X} + c_{LX}\hat{m}\hat{X}^d + c_{LY}(N-n)\hat{Y} + c_{LR}\hat{R} = \hat{L} . \tag{11}$$

The first term of the left-hand-side, $c_{LX}(n-\hat{m})\hat{X}$, is the amount of labor employed by the competitive fringe in the high-technology industry sector. There are $n-\hat{m}$ product groups where perfect competition prevails and $c_{LX}\hat{X}$ is the amount of labor employed in production per product group. The term $c_{LX}\hat{m}\hat{X}^d$ is labor hired by the $\hat{m}$ dominant firms. Each firm hires $c_{LX}\hat{X}^d$ workers and produces $\hat{X}^d$ units of output. Similarly $c_{LR}(N-n)\hat{Y}$ is the amount of labor devoted to the production of the (N-n) industries in the outside-goods sector and $c_{LR}\hat{R}$ is the number of workers employed in the production of the $\hat{R}$ units of R&D services.

World expenditure can be written as

$$\hat{E}=w_K\hat{K} + \hat{L} + \hat{m}\Pi^d-c_R\hat{R} \tag{12}$$

Because R&D services is an intermediate product, its value has to be subtracted from the value of final goods which is relevant to the calculation of expenditure. Then substituting (5) and (11) into (12) yields

$$\hat{E}(w_K,\hat{R}) \equiv (w_K\hat{K} + \hat{L} - c_R(w_K)\hat{R})[1-bT/(h(\hat{R})N)] \tag{13}$$

From demand considerations, we know that $\hat{X}=\hat{E}/(Np_X)$, $\hat{X}^d=\hat{E}/(N\alpha p_X)$ and $\hat{y}=\hat{E}/(Np_Y)$. Substituting these equations, and (10) into (11) yields the labor market condition:

$$f_1(w_K,\hat{R}) \equiv \left\{\frac{c_{LX}(w_K)}{Nc_X(w_K)}\,(n-bT/h(\hat{R})) + \frac{c_{LY}(w_K)(N-n)}{Nc_Y(w_K)}\right\}\hat{E}(w_K,\hat{R})+c_{LR}(w_K)\hat{R}-\hat{L} =0, \tag{14}$$

where the prices p_X and p_Y have been set equal to costs. Substituting (5) into (10) yields the zero profit in R&D condition

$$f_2(w_K,\hat{R}) \equiv - c_R(w_K)\hat{R}[1-e^{-\rho h(\hat{R})}] + e^{-\rho h(\hat{R})}b\hat{E}(w_K,\hat{R})(1-e^{-\rho T})/N = 0 \tag{15}$$

We will now establish the following:

Proposition 1: The dynamic general equilibrium model described in section II has a unique steady-state integrated equilibrium.

Proof To establish the proposition, we will show that the function $\hat{R}=R_1(w_k)$ implicitly defined by the labor market condition (15) and the expenditure condition (13) is upward sloping, the function $\hat{R}=R_2(w_k)$ implicitly defined by the zero profit in R&D condition (16) and (13) is downward sloping, and that these two functions intersect each other in the positive orthant.

In solving for a steady-state integrated equilibrium we can restrict attention to the subset of the positive orthant $S \equiv \{(w_K,\hat{R}) | w_K^1 \leq w_K \leq w_K^2,\ 0 \leq \hat{R} \leq R^w \text{ and } \hat{K}-c_{KR}(w_K)\hat{R} \geq 0\}$. Then for all $(w_K,\hat{R}) \epsilon S$, $\partial E(w_K,\hat{R})/\partial w_K \leq 0$; if not all of capital is employed in the R&D sector then strict inequality holds because not all of the increased factor income is saved. Since $\partial E/\partial w_K \geq 0$ and $dc_{LR}(w_K)/dw_K > 0$, it follows from (8) that for all $(w_K, \hat{R}) \epsilon S$, $\partial f_1(w_K,\hat{R})/\partial w_K > 0$. Increasing the relative rental rate increases the quantity demanded of labor in the world.

It follows from (6) and (7) that for all $(w_K, \hat{R}) \epsilon S$, $\partial f_1(w_K,\hat{R})/\partial \hat{R} < 0$. Increasing R&D means reduced world expenditure and a reduced quantity demanded of labor, given that the production of R&D services is highly capital intensive.

Using the fact that for all $w_K < w_K^2$, $\hat{K}/\hat{L} < c_{KR}(w_K)/c_{LR}(w_K)$, we can show that for all $(\hat{R}, w_K) \epsilon S$ satisfying $f_2(\hat{R},w_K)=0$, $\partial f_2(\hat{R},w_K)/\partial w_K < 0$. Increasing the rental rate on capital increases the cost of R&D services more than it increases world expenditure and the reward for winning an R&D race. Thus increasing the rental rate decreases the profitability of R&D.

Using (6) and the assumption that $h'(\hat{R}) < 0$, we can verify that for all $(w_K,\hat{R}) \epsilon S$, $\partial E(w_K,\hat{R})/\partial \hat{R} < 0$. An increase in R&D with w_K held fixed means that more resources are saved (go into R&D) instead of being spent on X and Y sector products, so world expenditure drops. From $\partial \hat{E}/\partial \hat{R} < 0$ and (4), it follows that for all $(w_K,\hat{R}) \epsilon S$, $\partial f_2(w_K,\hat{R})/\partial \hat{R} < 0$. Increasing R&D means reduced world expenditure, reduced dominant firm profits, a reduced reward for winning an R&D race and increased R&D costs. It follows that the profitability of R&D falls as more resources are devoted to R&D.

From the implicit function theorem, it follows that in S, $dR_1(w_K)/dw_K>0$ and $dR_2(w_K)/dw_K<0$. From the definitions of w_K^1 and w_K^2 it follows that $f_1(w_K^1,0)<0$, and $f_1(w_K^2,0)>0$. By the intermediate value theorem, there exists $w_K^0\epsilon(w_K^1,w_K^2)$ such that $R_1(w_K^0)=0$ (w_K^0 represents the traditional Heckscher-Ohlin equilibrium rental rate). By definition of w_K^2, $R_1(w_K^2,K)=R^w$, $E(w_K^2,R^w)=0$ and $f_2(w_K^2,R^w)<0$. Since $f_2(w_K^2,0)>0$, by the intermediate value theorem there exists $\bar{R}\epsilon(0,R^w)$ such that $R_2(w_K^2)=\bar{R}$. Together these results guarantee that the $R_1(w_K)$ and $R_2(w_k)$ functions must have a unique intersection in the subset S of the positive orthant. **Q.E.D.**

This steady state integrated equilibrium is illustrated by point B in Figure l. The Heckscher-Ohlin equilibrium corresponds to point A. The Heckscher-Ohlin equilibrium emerges from our model when there is no patent protection (T=0) and therefore no firm has any incentive to engage in R&D activities ($\hat{R}=0$). The steady-state equilibrium rental rate, $\bar{w}_K^2$, is higher than the Heckscher-Ohlin equilibrium rental rate, w_K^0, because of our assumption that the R&D sector is relatively capital intensive. As a result, capital must be rewarded for moving into the R&D sector.

Although the production structure of the present model is characterized by properties of the standard Heckscher-Ohlin model, there is continuous introduction of new, high-quality products in the spirit of the Schumpeterian description of creative destruction. Firms engage in R&D races, discover new products, earn temporary monopoly profits, and when their patents expire they are replaced by other firms. The world economy experiences endogenous growth and the utility of the world representative consumer increases continually due to product innovation.

IV. Trade and Investment Patterns

The properties of the steady state equilibrium can be explored further by using a factor price equalization (FPE) set diagram (Figure 2). The amount of capital in the home country is measured on the ordinate and the amount of labor in the home country is measured on the abcissa. The world endowment of capital and labor is given by the diagonal OO^* of the box diagram. Vectors $OQ_1=O^*Q_1$, $Q_1Q_2=Q_1'Q_2'$ and $Q_2O^*=OQ_2'$ represent the amounts of capital and labor employed in the R&D services, high-technology industry and outside-good sectors, respectively. Assumption (1) justifies the relative slopes of these vectors. The factor price equalization set is defined as the set of all factor endowment distributions between the two countries such that each country can fully employ its resources, and is represented by the area enclosed by hexagon $OQ_1Q_2O^*Q_1'Q_2'$.

The high-technology industry vector Q_1Q_2 can be decomposed into two segments, Q_1X, which is the amount of world resources employed by the $\hat{m}$ dominant firms, and XQ_2, which is the amount of capital and labor employed by the $n-\hat{m}$ competitive industries in the sector.

Suppose that the distribution of factor endowments between the two countries is located in the FPE set and that the home country is capital abundant ($K/L > K^*/L^*$). In Figure 2 the home country factor endowment point, F, is in the quadrilateral $OQ_1Q_2O^*$, which is the upperhalf of the FPE set. Draw the parallelogram FP_XOP_Y and the line RP_X which is parallel to Q_1Q_2. It is easy to see that the home country's endowment vector OF equals the summation of $OR + RX_1 + X_1P_X + P_XF$, where OR is the employment vector for home-country R&D services, RX_1 is the employment vector of the m dominant firms, X_1P_X is the employment vector of high-technology goods produced competitively, and $P_XF = OP_Y$ is the employment vector of outside goods. By drawing the parallelogram $FP_Y'O^*P_X'$ and line $P_X'R'$ we can determine the corresponding vectors of the foreign country.

Denote with s the fraction of world R&D services which corresponds to the home country: $s \equiv R/\hat{R}$, where R corresponds to vector OR and $\hat{R}$ is represented by vector OQ_1 in Figure 2. Assume that R&D services are not traded, and that the manufacture of high-technology goods produced by dominant firms takes place in the country of discovery during and after their patents expire. The steady-state expected number of home country dominant firms m is given by $m=\hat{m}R/\hat{R}$, where $\hat{m}$ is the number of world dominant firms and $R/\hat{R}$ is the probability that some home-country firm wins a typical R&D race. Substituting $R=s\hat{R}$ in the above expression we get $m=s\hat{m}$. The employment vector of m dominant firms is equal to $s(Q_1X)$, where Q_1X corresponds to resources devoted to the production of $\hat{m}$ dominant firms. Moreover, in the steady state, all high-technology-industry products that are competitively produced were once produced by dominant firms. The employment vector devoted to the production of high-technology goods whose patent has expired is $s(XQ_2)$ for the home country, where XQ_2 is the vector of world resources allocated to the production of competitively produced goods in sector X.

In Figure 2, RP_X is parallel to Q_1Q_2; triangle OQ_1X is similar to triangle ORX_1; triangle OXQ_2 is similar to triangle OX_1P_X and triangle OQ_1Q_2 is similar to triangle ORP_X. Consequently if $s = OR/OQ_1$, then the home-country resources devoted to dominant-firm production is $RX_1 = s(Q_1X)$, the resources devoted to competitively-produced, high-technology goods is $X_1P_X = s(XQ_2)$ and total resources devoted to high technology sector is $RP_X = s(Q_1Q_2)$. Thus, the home country devotes the same fraction of world resources to R&D services, manufacturing of dominant firm products and manufacturing of high-technology goods produced competitively.

In Figure 2, given the endowment point F, point P_X is uniquely determined by the requirements that R&D services are non traded and that all goods in the high-technology sector are produced in the country of discovery. The reason is the following. Given the integrated equilibrium capital:labor ratios in the three sectors, if the home county devotes more or less resources than P_XF to the production of outside goods sector, point P_X will necessarily lie off line OQ_2 which implies that the new vector $RP_X \neq s(Q_1Q_2)$, and one of the above mentioned assumptions will be violated. The above analysis establishes the following:

Proposition 2: If the factor endowment point F lies in the subset $OQ_2O^*Q_2'$ of the factor price equalization set $OQ_1Q_2O^*O_1'Q_2'$, then the steady state integrated equilibrium can be reproduced with all high-technology goods manufactured in the country of discovery during their patent length and after their patent expires.

Figure 3 shows an endowment point F inside triangle OXQ_2. Assuming that dominant-firm production takes place in the country of discovery, multiple patterns of production can occur because the number of "tradeable" sectors exceeds the number of factors of production. Following Helpman (1984) we will look at equilibria characterized by the minimum number of products experiencing product cycles and the minimum number of multinational firms. This assumption is arbitrary, but it can be justified on the grounds that there are costs of shifting production abroad and we are looking at the limit of a sequence of economies with relocation costs as these costs approach zero.

In Figure 3, the home country's capital-labor vector OF is such that it cannot produce all the competitive products after their patents expire. To reproduce the integrated equilibrium draw line RX_1FF_1 which is parallel to Q_1Q_2. If OR is the home country capital-labor vector devoted to R&D services, then $RF_1=RX_1+X_1F+FF_1$ is the world vector of capital and labor allocated to production of all high-technology goods discovered in the home country. Vector RX_1 represents factor employment by the m home-dominant firms. Vector X_1F is the amount of home-country capital and labor allocated to the production of high-technology goods after their patents expire. These products were discovered in the home country and their production remains in the home country. In other words, vector X_1F denotes products which do not experience product cycles. However, the factors represented by X_1F are insufficient to maintain home-country production of all high-technology goods discovered in the home country. Vector FF_1 is the amount of foreign-country resources devoted to the production of high-technology goods produced competitively and discovered in the home country. These products are discovered in the home country and they are produced in the home country for the duration of their patents. During this period of time they are exported to the foreign country. However, when their patents expire these goods are produced in the foreign country and are exported back to the home country. Thus the equilibrium associated with endowment point F exhibits product cycles in high-technology products.

In this production pattern unique? Draw line X_2F which is parallel to OQ_2'. In general, for any point which lies on segment X_1X_2 one can draw a line which is parallel to Q_1Q_2 and determine a new point R which is consistent with the integrated equilibrium. Notice however that any point in X_1X_2 will be associated with more home country R&D than OR and more products experiencing cycles compared to point X_1. Thus, concentrating on the minimum amount of products experiencing cycles, the pattern of production described in Figure 3 is unique.

Proposition 3: If the factor endowment point F lies in either of the subsets OXQ_2 or $O^*X'Q_2'$ of the factor price equalization set $OQ_1Q_2O^*Q_1'Q_2'$, then in the integrated equilibrium with all high-technology products manufactured in the country of discovery for the duration of their patents, some high-technology products must experience product life cycles. The fraction of products which experience product cycles increases in the capital:labor ratio of the home country.

If the endowment point lies in triangle OQ_rX, then an argument analogous to that used in proposition 3 shows that the home country allocation of factors to the production of high-technology goods is given by $RF < RX_1$. Hence the home-country production of these goods is insufficient to supply the world's demand for high-technology goods produced by dominant firms. More generally, we can show

Proposition 4: If the factor endowment point F lies in either of the subsets OQ_rX or $O^*Q_r'X'$ of the factor price equalization set $OQ_1Q_2O^*Q_1'Q_2'$ then in the integrated equilibrium some high-technology products must be produced by multinational firms and some high-technology products must experience product life cycles.[4]

Constant returns to scale in manufacturing allows three different institutional interpretations of the equilibrium described in Proposition 4. First, it is possible that all home-dominant firms operate plants in both countries and each multinational firm produces a fraction equal to FF_1/RF_1 of its total output in the foreign country. In other words, there is multiplant production of home-country based multinationals and these firms participate in R&D races in the home country. Notice that this institutional interpretation requires that the assumption of minimum internationalization means the minimum amount of capital and labor employed abroad instead of the minimum number of firms becoming multinationals. The second interpretation results from the assumption that there is no multiplant production and each

[4]For a formal proof, see Dinopoulos et al (1990).

dominant firm produces in one country. According to this interpretation, a fraction FF_1/RF_1 of m domestic firms locate their manufacturing activities in the foreign country. These firms participate in R&D races in the home country and they maintain subsidiaries in the foreign country for the duration of the product patents. Moreover their monopoly profits are repatriated to the home country in the form of goods exported by the foreign country. Third, the model allows the generation of technology license agreements. The home-country firm which discovers a good sells its patent rights to a foreign-country firm, which manufactures the newly discovered good in the foreign country, markets the good internationally for the duration of its patent and pays instantaneous royalties equal to instantaneous profits. The model allows any or all combinations of the three institutional arrangements to coexist.

The model highlights the role of factor endowments in determining the pattern of production, trade and investment in the steady state equilibrium. Consider again Figure 3 and notice that as long as the endowment point F lies in the interior of the FPE set $OQ_1Q_2O^*Q_1'Q_2'$ both countries have dominant firms. This means that there is always intra-sectoral trade because the world consumes <u>all</u> dominant-firm products. As the difference in capital:labor ratios between the two countries increases, the degree of "internationalization" of the capital-abundant country increases. Thus, as the capital:labor ratio of the home country increases from OQ_2 to OX, in addition to intrasectoral trade, a larger fraction of home-country products experience product cycles and their production shifts to the labor abundant country. When the capital labor ratio of the home country equals OX all its products experience product cycles after their patent expires. As the capital-labor ratio of the home country approaches OQ_1 from OX, in addition to intrasectoral trade, all products discovered in the home country are produced abroad after their patent expires, and a higher fraction of home country dominant-firm production shifts to the labor abundant country.

V: The Role of Assets and Intersectoral Trade.

The pattern of intersectoral trade depends on the factor content of world and country consumption, in addition to the pattern of production which was analyzed in detail in the previous subsection. The consumption point in the economy depends on income from assets. Steady-state consumption expenditures are $\hat{E} = w_K\hat{K} + \hat{L} + \rho\hat{A}$ where $\hat{A}$ represents the steady-state assets associated with the integrated equilibrium. Figure 4 illustrate these expenditures. The value of the world endowment point O^{*} is $w_K\hat{K} + \hat{L}$. The value of the increment $O^{*}O^{**}$ of capital and labor represents the amount of asset income spent on current consumption $\rho\hat{A}$; hence the point O^{**} represents the value of current consumption, $w_K\hat{K} + \hat{L} + \rho\hat{A}$. The vector $O^{*}O^{**}$ is drawn with the same slope as OQ_1, since the asset income represented by $O^{*}O^{**}$ is generated by capital and labor used to produce past R&D, and because the R&D capital:labor ratio is constant in the steady state and equal to the slope of OQ_1. Consequently, OO^{**} represents the present-value-equivalent factor content of today's world consumption.

Let A be the value of assets owned by the home country. Then the home-country consumption expenditures equal $w_K K + L + \rho A$. The value of these expenditures is represented by the point $\bar{F}$. This point is constructed by adding to the endowment point F (which has value $w_K K + L$) a vector $F\bar{F}$ of capital and labor with value equal to ρA and with slope equal to the slope of OQ_1. $O\bar{F}$ represents the present-value-equivalent factor content of today's home-country consumption.

Using the fact that all consumers have identical homothetic preferences, the asset-adjusted factor content of home-country consumption must lie on the diagonal OO^{**} and must cost as much as point $\bar{F}$. The dashed line through $\bar{F}$ with slope $-1/w_K$ defines the set of asset-adjusted consumption points which cost as much as $\bar{F}$. Thus the asset-adjusted factor content of home-country consumption is given by the vector $O\bar{C}$ in Figure 5. The home country's asset-adjusted endowment is capital abundant, as can be seen by the location of $\bar{F}$ above the diagonal OO^{**}, and the home-country trades capital for labor.

When consumers buy today's high-technology goods and goods in the Y sector, they are paying for today's X sector and Y sector factors of production (Q_1Q_2 and Q_2O^* in figure 5), as well as past R&D capital-labor that went into discovering the products produced by the $\hat{m}$ dominant firms today. The sum of the values of the vectors OQ_1 and O^*O^{**} represents payments to past R&D efforts, captured as dominant-firm profits in today's market. When consumers buy today's products, they are paying for today's production costs and today's profits which are incorporated in today's market prices. Today's profits can be attributed to past R&D efforts, not current R&D efforts.

How much of the asset-adjusted factor content of today's aggregate production OO^{**} can be attributed to the home country? Since assets are traded internationally, foreign country consumers can finance home country R&D races and thus end up, in effect, owning home-country R&D inputs. Thus products that are produced by home country factors may actually be owned by foreign country consumers (prior to any trade in goods) and this should be taken into account when calculating the factor content of international trade in goods. The asset-adjusted factor content of today's home country production must lie on a line with slope $-1/w_K$ and horizontal intercept $w_K K + L + \rho A$, which is equal to home country expenditure. Today's home country production is produced by the X sector production factors (given by RF in Figure 5) and some fraction of the past R&D production factors OQ_1' owned by the home country. Since the line $RF + \lambda OQ_1'$, $\lambda \epsilon 0,1)$ intersects the asset-adjusted home country budget line at a single point ($\bar{F}$ in Figure 5), $O\bar{F}$ represents the asset-adjusted factor content of today's home country production.

Given the previously described framework, we can show the following:

Proposition 5: If a country's physical endowment renders it capital abundant relative to the aggregate asset-adjusted factor endowment, then the country is a net exporter of capital-intensive goods in the steady-state equilibrium.

Proof: In terms of Figure 5, the home country's physical endowment is capital abundant relative to the aggregate asset-adjusted factor endowment if the physical endowment (point F in Figure 6) lies above the diagonal OO^{**}. Adding on to this vector OF a fraction of the vector $O^{*}O^{**}$ to get the home country's asset-adjusted factor endowment (point $\bar{F}$) means moving farther away from the diagonal OO^{**}. Since commodity trade involves moving to the diagonal OO^{**}, (all consumers have identical homothetic preferences) the home country must trade capital for labor, establishing the proposition. **Q.E.D.**

Proposition 6: If a country's physical factor endowment renders it labor abundant relative to the aggregate asset-adjusted factor endowment and if the country has a sufficiently small share of the world's assets, then it is a net exporter of labor-intensive goods.

Proof: In terms of Figure 6, a country is labor abundant relative to the aggregate asset-adjusted factor endowment if its physical endowment of capital and labor (point F in Figure 6) lies below the diagonal OO^{**}. If the country has a sufficiently small share of the world's assets, then its asset-adjusted factor endowment $\bar{F}$ will be close enough to F so that $\bar{F}$ is also below the diagonal OO^{**}. Since commodity trade involves moving to the diagonal OO^{**}, the country must trade labor for capital, establishing the proposition. **Q.E.D.**

Figure 7 illustrates an interesting third possibility, namely, that a country which is labor abundant relative to the aggregate asset-adjusted factor endowment, is also an asset-adjusted net exporter of capital-intensive goods. In Figure 7, the home country static endowment of capital-labor (point F) renders it a relatively labor abundant country (compared to the aggregate asset-adjusted endowment 00^{**}). But as drawn, the home country consumers own all the worlds assets and since R&D is a relatively capital abundant when its assets (ownership of foreign R&D capital and labor) are taken into account. Thus assets can serve to reverse the traditional Heckscher-Ohlin relationship between relative factor abundance and the factor content of international trade.

VI: Conclusions

The present paper constructed a dynamic general equilibrium model of international R&D competition in which higher quality products replace lower quality ones. Product innovation follows closely Schumpeter's (1942) description of product creation and replacement. The structure of production incorporates the insights of the traditional Heckscher-Ohlin trade model.

We employed the model to analyze the rich pattern of trade and investment in the steady state equilibrium in which R&D expenditures and the rate of product innovation are constant over time. Factor endowments determine the extent of intersectoral trade and the set of products which experience product cycles. The model generates intra-sectoral trade and multinational activities. The extent of multinational activities depends on factor endowment differences and can take the forms of multiplant manufacturing, single plant manufacturing in one country with R&D research in another, or licensing of manufacturing of newly discovered goods. When there is no patent protection, R&D activities stop and the model generates the traditional Heckscher-Ohlin model of international trade.

Segerstrom, Anant and Dinopoulos (1987) have analyzed the Ricardian structure of production in a model which incorporates an identical process of product innovation and replacement. Issues concerning commercial policy, welfare considerations and outside of steady-state analysis in high-technology industry have been examined by Dinopoulos, Oehmke and Segerstrom (1989) in a partial equilibrium framework. Segerstrom (1990) was endogenized the imitation process by incorporating dynamic subgame strategies which allow collusion between imitators and innovators.

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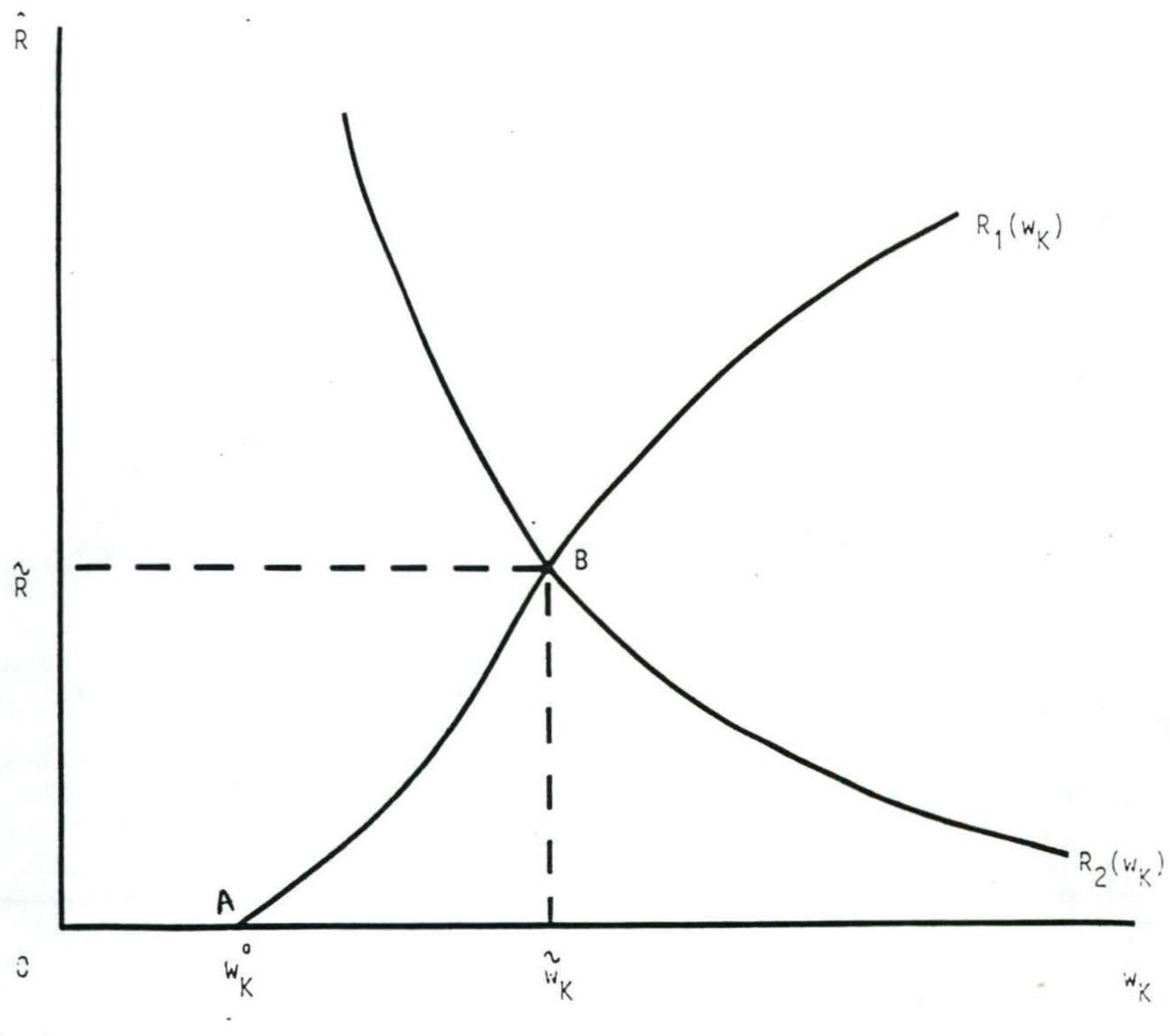

FIGURE 1: The Steady State Integrated Equilibrium

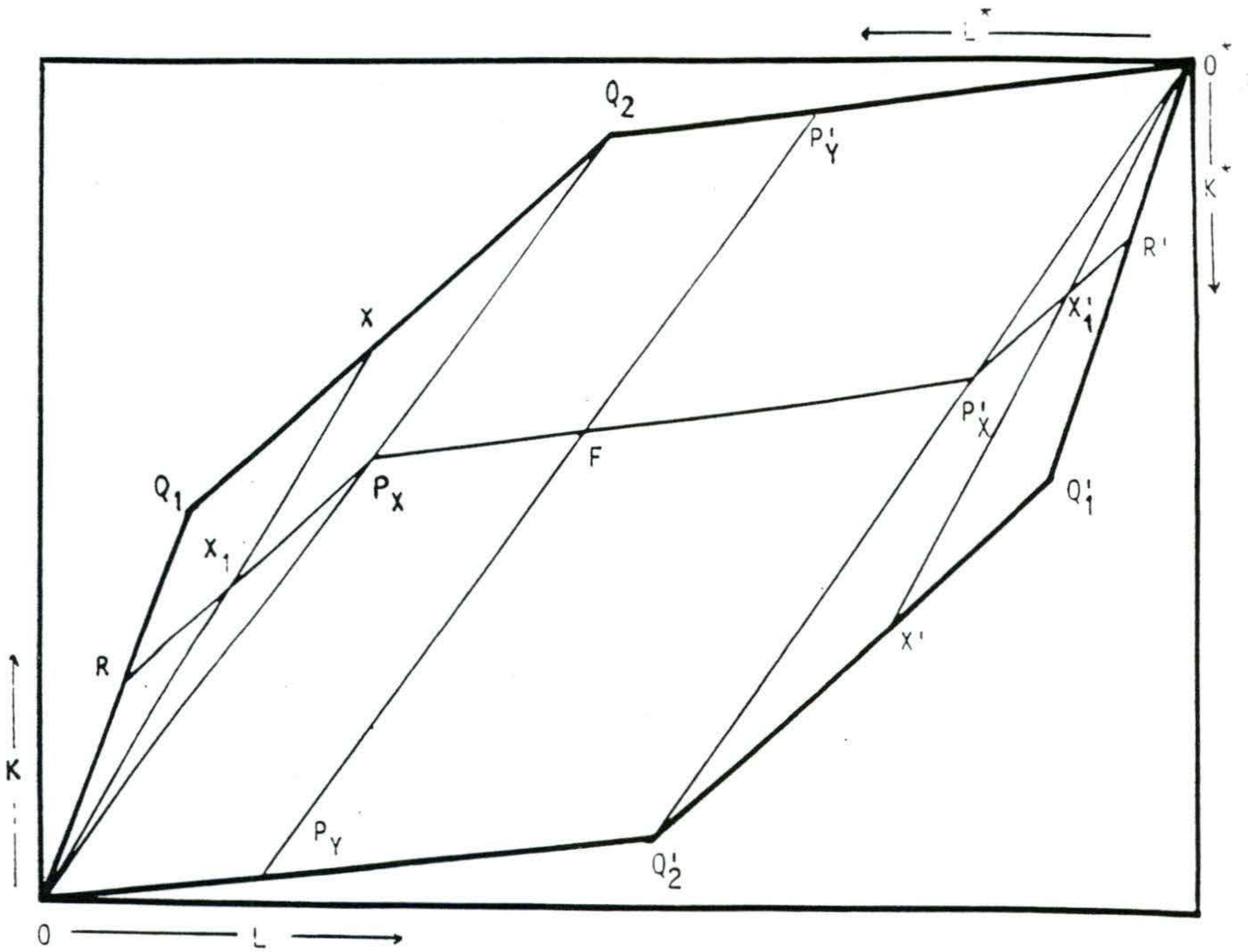

Figure 2: Production Pattern without Product Cycles and No Multinationals

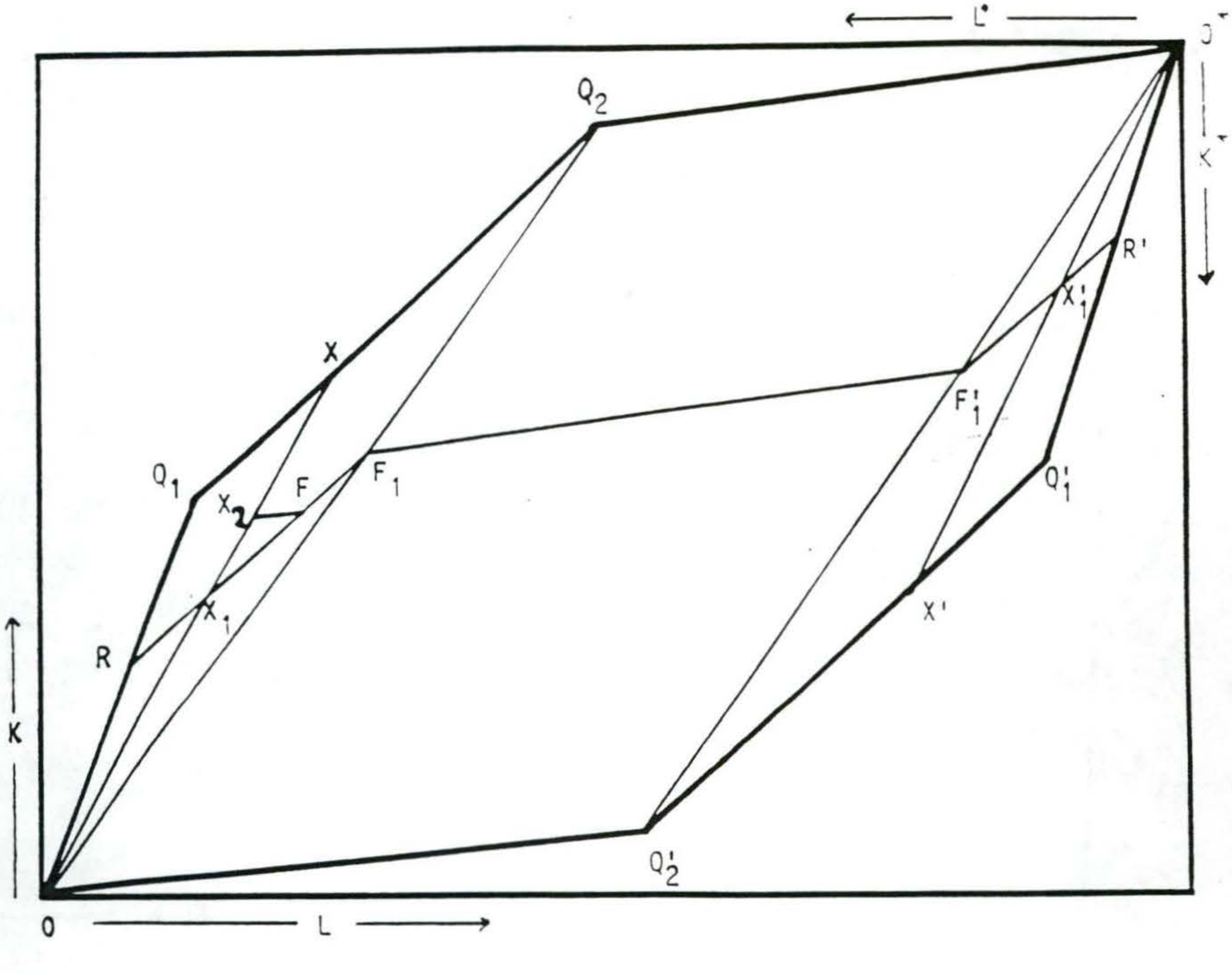

Figure 3: Production Pattern with Product Cycles

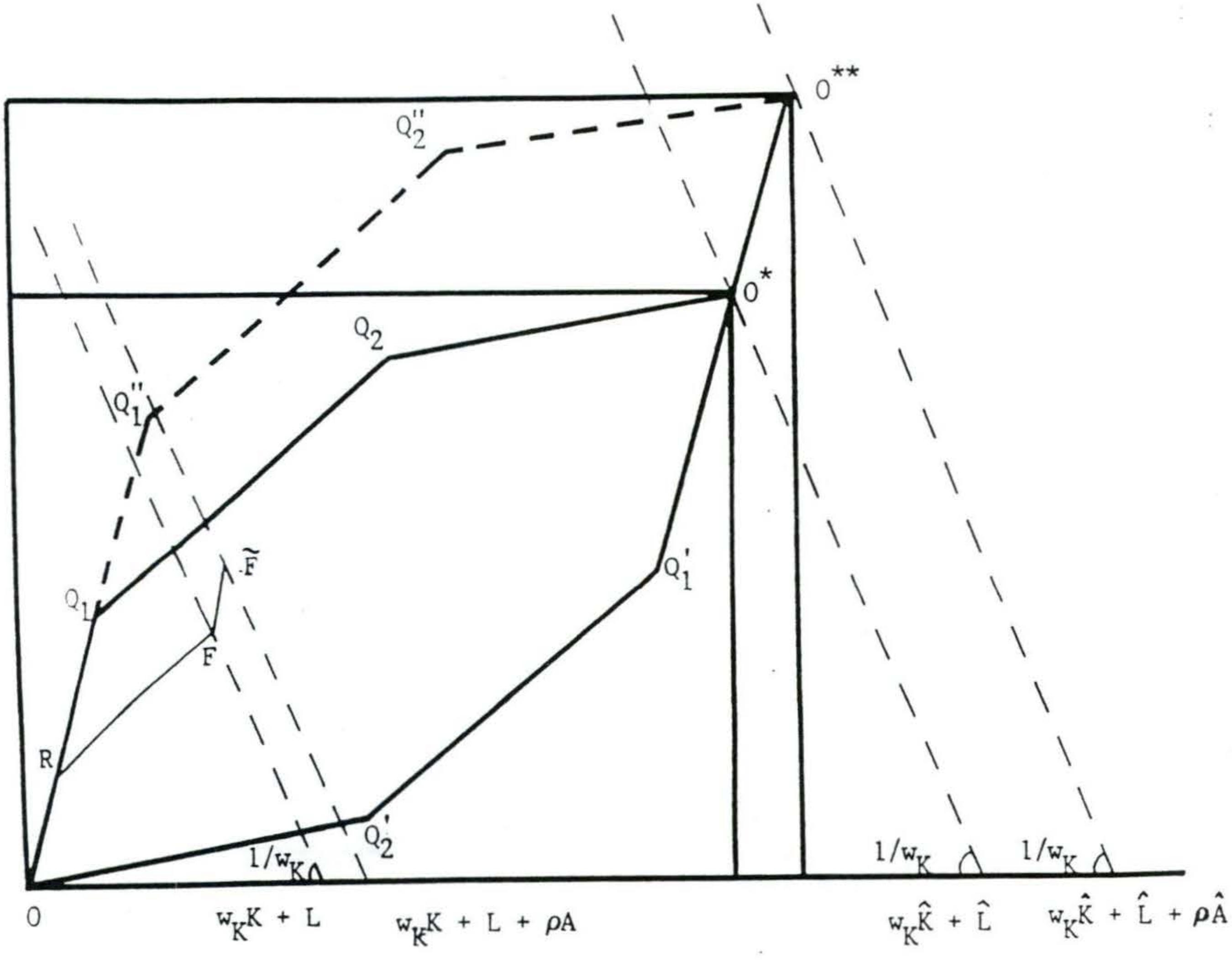

Figure 4: The Pattern of Intersectoral Trade with Assets

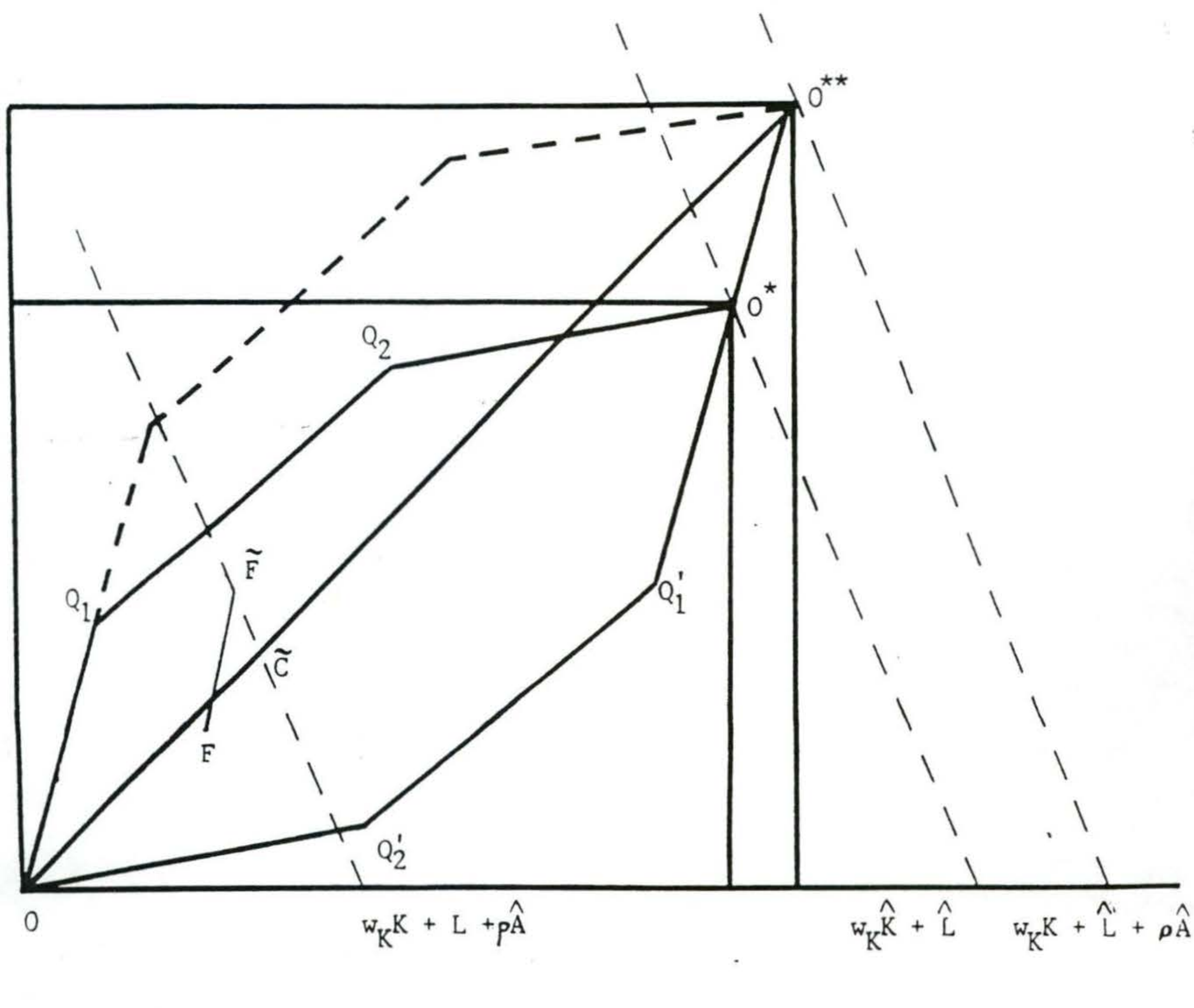

Figure 5: Assets Can Reverse the HOS Pattern of Intersectoral Trade