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R&D ACTIVITIES AND THE TECHNOLOGY GAME: A DYNAMIC MODEL OF U.S.-JAPAN COMPETITION

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ABSTRACT

This paper presents an international comparison of R&D activities in basic and applied research. The commonly-held view that Japan is not spending much on basic technology development cannot be empirically substantiated from the study of the historical trends. However, the fact that in the U.S.A. the largest proportion of industrial R&D expenditures is spent on the defense and aero-space related industries (60%), while Japan is spending the largest proportion (60%) on the chemical, electronics, communication and automobile industries, may indicate that in effect Japan emphasizes the development of applied technology.

The second part of the paper is to show how two countries, one with heavy R&D activities in basic technology (the U.S.A.) and the other with heavy R&D activities in applied technology (Japan), can compete in the world market with their productivity differences in basic and applied fields. A simple model of differential game is presented to explain how Japan can increase the market share by utilizing both the informational and productivity efficiencies.

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by

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I. Empirical Trends

1. Introduction

Leading countries in technology like the U.S.A., Germany, France, and the United Kingdom have generated scientific breakthroughs and innovations in the past via endogenously determined Research and Development (R&D) activities, whereas latecomers like Japan, South Korea and most of the developing countries have adopted the policy of technology importation from the technological leaders. The basic characteristic of the technological leaders' R&D activities is that they tend to invest relatively larger amounts of funds in basic research. The latecomers, on the other hand, invest relatively larger sums of money in applied research and development. First by imitation, then by improvements on the processes and products imported, the latecomers have gained a competitive edge in export markets as they can now produce the same (or similar) goods at a lower cost and export them to the world market. This aspect of intra-industry trade competition can best be explained in terms of the comparative cost analysis of basic and applied innovations in the trading countries.

International competition often depends on competition to develop technologies specific to the products traded--the technology game. In this paper, after reviewing some R&D trends in the U.S.A., Japan and European countries, we present a model of technology (differential) game between two countries. It is becoming increasingly clear that modern technologies are the results of science-related R&D activities (see Freeman [1982]). We first review the post-World War II Japanese R&D activities, emphasizing some unique characteristics. International comparisons of R&D expenditures on basic vs. applied research will then be presented.

The differential game model presented in this paper has several unique characteristics in that the firms (monopolistic) in the two countries engage in the production of a similar product and in the exportation of the product to the world market. These firms also engage in R&D activities: the firm in the first country produces both basic and applied technologies or technological innovations, whereas the firm in the second country imports basic technology from the firm in the first country and makes improvements in the form of process innovations. Production and generation of these innovations are basically dynamic and the firms in the two countries engage in the technology differential game of long-run profit maximization. More specifically we consider the effects of the three parameters on the market share outcome: (1) the index of diffusion of basic technology; (2) the index of relative efficiency of applied research; and (3) the index of cost sharing of basic research. The model describes a variety of cases, depending on whether the game played is in terms of a closed or open strategy. Under the closed strategy game, the firm with the advantages in applied research may not necessarily dominate the export market.

1. The Japanese R&D Activities

For the post-World War II period Japanese R&D activities may be divided into three subperiods: (1) importation of foreign technology; (2) adaptation and improvement of foreign technology; and (3) development of indigenous Japanese technology--high technology.

The 1950s was characterized by the marked increase in the import of foreign technology into Japan. The average annual rate of increase in foreign technology imports was more than 30%. The ratio of the amount of expenditures on foreign technologies to the total R&D expenditures was 0.45--nearly half of the total R&D activities was based on foreign technologies. This ratio eventually went down to 0.24 in the 1960s, and to 0.10 in the 1970s, as Japan gradually adopted different R&D strategies (see Table 1).

One interesting, and also unique, aspect of the Japanese policy regarding the importation of foreign technology was that the government gave import permission to only a small number of large firms. The government did not permit any firm to monopolize the foreign technology, nor did it allow every firm to obtain or seek foreign technology. Here the government's aim was to artificially create oligopolistic cooperation and competition. This policy was adhered to until the 1968, when the government had to completely lift the ban on technology import. The number of annual permissions to import technology jumped from 100 in the 1950s to over 1,000 in 1968 (see Table 2).

Table 1. Trends of Foreign Technology Imports in Japan

	(A) Annual Percent Change in the Importation	(B) Total R&D Expenditure Growth Rate	Import of Foreign Technology Total R&D Investment	Elasticity = A/B
1953-59 (Average)	30.8%	25.6%	0.449	1.61
1960-69	20.7	21.1	0.240	0.97
1970-74	9.8	20.6	0.165	0.53
1975-79	6.0	10.9	0.121	0.73

Source: Statistical Division, Japanese Prime Minister's Office and Bank of Japan Statistics. See also Wakasugi [1983].

Table 2. Number of Permissions of Technology Import

1950-1959 (Average)	103
1960-1967 (Average)	469
1968	1,061
1969	1,154

Source: Ministry of Science and Technology, Government of Japan.

Japanese R&D expenditures grow at a high rate of over 20% per year in the 1960s. At the same time, the sales of Japanese companies also grew at a rapid rate. Among the industries which enjoyed phenomenal growth were the chemical, textile, petroleum, machinery, consumer-durable, electric and automobile industries. In these industries, R&D expenditures went towards improvements and adaptations of processes rather than basic research. Figure 1 shows the trends of R&D expenditures and the expenditures on foreign technology import in relation to total sales in the manufacturing sector.

There is another aspect of the Japanese Government's role in R&D activities. The government granted tax credits and subsidies to several selected firms in each industry. A rough estimate of the extent of these credits and subsidies is as high as 9.1% of all R&D expenditures in the 1960s. (See Table 3.) In particular, the amounts of tax credits consisted of 8.7% of total R&D expenditures in the 1960s. These subsidies are considered as direct investment made by the Japanese government.

In the early 1970s, the character of Japanese R&D activities changed dramatically, R&D activities shifted from the chemical, steel and other heavy industries to the so-called "high technology" industries. These include the computer, semi-conductor and electronics industries. This is the area of endogenous technical progress adopted by the Japanese firms. At the same time, Japan

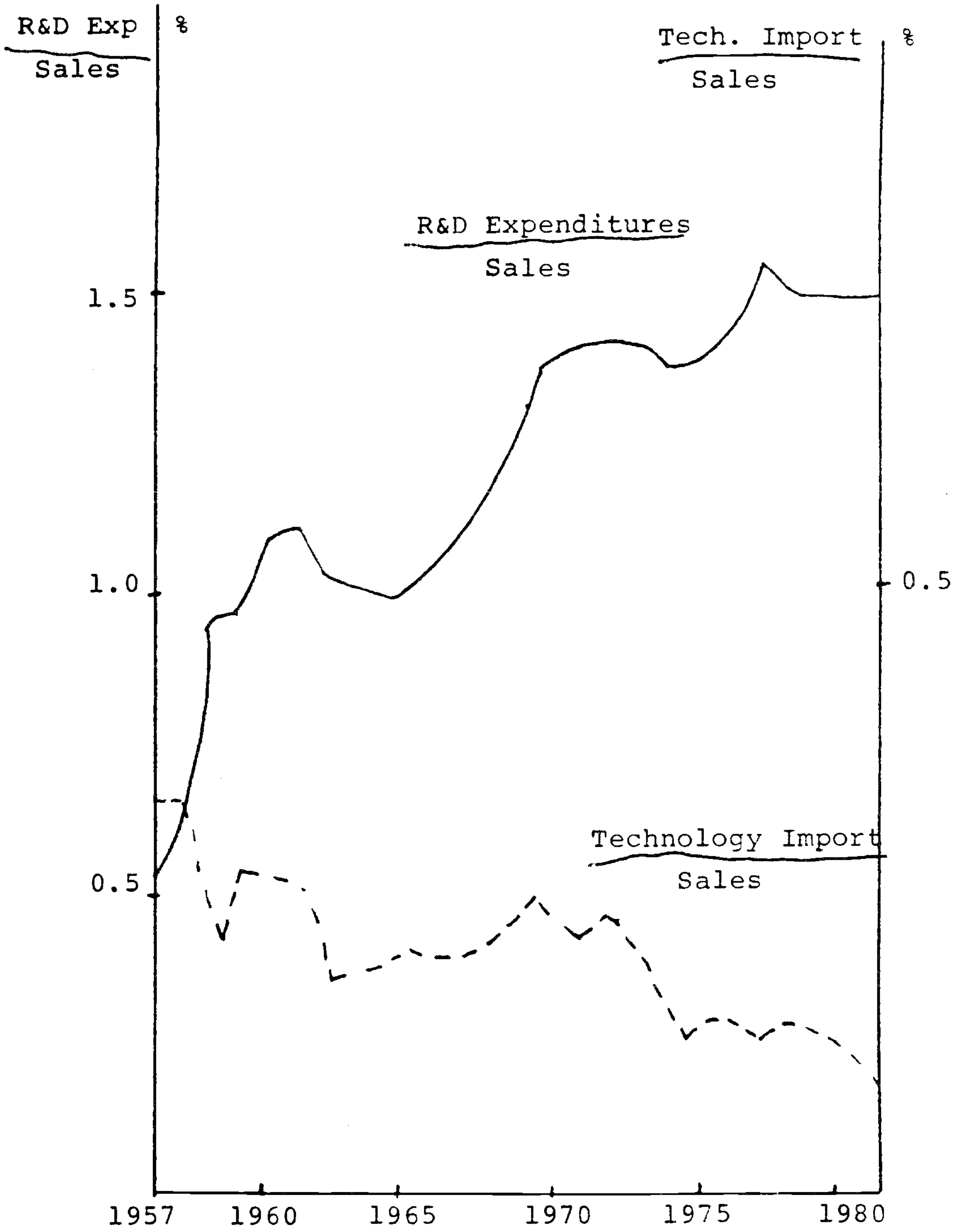

Figure 1. Trends of R&D Expenditures and Foreign Technology Import

Source: Calculated from Prime Minister's Office "Report on Science and Technology," Government of Japan, 1982.

Table 3. Government's Tax Credits and Subsidies

	(1) $\frac{\text{Subsidies}}{\text{Private R\&D Exp.}}$	(2) $\frac{\text{Tax Credits}}{\text{Private R\&D Exp.}}$	(1) + (2)
1960-64	0.4%	8.7%	9.1%
1965-69	1.2	3.1	4.3
1970-74	1.7	2.0	3.7
1975-80	1.4	1.4	2.8

Source: Wakasugi [1983].

started to export technologies abroad, particularly to other Asian countries. The ratio of technology exports to technology imports exceeded unity in the 1970s, indicating that Japan was rapidly producing its own technologies and innovations, not only for domestic use but also for export purposes.

Cooperation and Competition--Japanese Industrial Policy

The most misunderstood aspect of Japanese industrial and technology policies is the belief that government policies are solely responsible for the success of the economy. The role of the Japanese Government in industrial policy is that it takes a "dual" character.

First, the government serves as the guardian to certain industries. It selects a small number of important and powerful companies in the industry so as to protect them from domestic and foreign competition. Those companies selected by the government are required to work cooperatively with other companies in the group. These selected firms jointly cooperate to produce new technologies or new innovations. The advantage of the cooperation of the selected firms lies in the fact that they can exploit economies of scale and increasing returns. One company alone may not be able to develop a drastic innovation, but five companies together may be able to do it. A good example of this kind of cooperative effort is the development of the so-called fifth generation computers. The government's role in the cooperative technology game is socially accepted in Japan, while such a practice may be completely unacceptable in other countries, like the U.S.A., for example, where omission or exclusion of some companies might result in a court case for the government. One can imagine a New York Times headline for such a case!

The other aspect of the role of the Japanese Government is the supervision of the domestic market competition among those companies selected. This "dual" role usually comes at the second stage, after the successful innovation has occurred. Once a new technology is developed, the government suddenly changes its role to that of the promoter of competition among the selected firms. The second stage is the stage in which each firm goes back to their own factories with the new technology and makes their own products and competes in the domestic and world markets. The importance of this competitive stage should never be under-emphasized. The success of the Japanese industrial policy comes from the well-balanced roles of cooperation in the first stage and of competition in the second stage.

2. International Comparisons

We must first be aware of the difficulties inherent in an attempt to make international comparisons of economic statistics. Different countries use different definitions for the same concept, or use the identical definitions for different concepts. The concept of "basic" research is a case in point. "Basic research expenditures" in one country may be in fact applied research expenditures in another country. Nonetheless, it may be useful to make international comparisons on the basis of such expenditures.

Table 4 shows the distribution of the central government's R&D expenditures in five advanced countries in recent years. It is seen that U.S.A., U.K., and France are spending a large fraction of their total R&D expenditures on defense and military R&D, while Japan's expenditure on this category is extremely small, only 2.4%. On the other hand, the expenditure for the general scientific purposes is very large in Japan (63.8%) and in Germany (48.6%). Another interesting aspect is that a large fraction of the government expenditures on R&D is for the development of industrial technology in France, 66.7%.

Table 5 is an international comparison of the government's R&D funding distributed to various institutions. Industries in all countries compared, except Japan (5%), received a large sum of money: U.S.A. = 48.2%, U.K. = 39.0%, W. Germany = 29.5%, and France = 25.2%. One way of interpreting this apparent contradiction for Japan is that the Japanese method of financing R&D activities is different from other countries. Expenditures are usually paid to nonprofit organizations rather than to industries directly. These organizations include government enterprises related to space exploration, atomic energy research, super computer research, etc. This practice is understandable in view of the Japanese government's policy discussed in the previous section.

An international comparison is made in Table 6 for the three types of research expenditures, basic research, applied research, and development. Universities in Germany engage in only basic research, while Japanese universities do applied research as well as basic research. In fact, Japanese universities engage in applied research to a much greater extent than universities in the other countries, 35.8% as compared with 28.1% for the U.S.A., 10.6% for W. Germany and 3.6% for U.K. The apparent contradiction in Table 5, that Japan spends little on industrial research, can now be reconciled from the data in Table 6. We saw that in Table 5 a large fraction of government expenditures (45%) in Japan goes to the universities and that amount is also used for applied research, maybe sometimes for industries. Looking at Table 6, one finds that industrial research activities in the U.S. and Japan are very similar. Both spend over 75% on development, nearly 20% on applied research and less than 5% on basic research. The overall comparison of basic, applied and development expenditures in the five countries is presented in Table 7. It shows that overall, Japan, U.K. and U.S.A. have a similar distribution, while W. Germany and France are spending relatively more on basic research.

Table 8 focuses on the U.S.A.-Japan comparison of industrial R&D. In the U.S.A. the largest amount is spent on the aero-space related industry (24.4%), followed by the electronics and communication industry (21.8%). On the other hand, Japan is spending the largest proportions on the chemical industry (20%), electronics and communication (15.6%), automobile production (15.3%), and household electric appliances (12.7%) respectively. It should be noted that the Japanese research effort is aimed at the areas where Japan can compete in the inter-national market.

In Table 7, we observe that the corporation's R&D activities in the U.S.A. and in Japan are very similar. Over 75% of expenditures is for development, nearly 20% is for applied research, and less than 5% is for basic research. Table 9a and 9b compares the largest twenty companies in the U.S.A. and Japan in 1980. They are ranked according to the amount of R&D expenditures. It shows that prominent companies in both the U.S.A. and Japan invest large sums of money for R&D.

We expect that international competition among these big firms crucially hinges on how fast they can develop inventions and innovations. The ability to dominate the international market crucially depends on how fast they can develop new products and/or new process innovations. To this type we now turn our attention in Part II.

Table 4. Distribution of Government's R&D Expenditures in Various Countries

	U.S.A. (1977)	United Kingdom (1975)	W. Germany (1975)	France (1977)	Japan (1979)
Defense & Military	49.6%	45.4%	12.0%	29.9%	2.4%
Space & Aero Space	12.8	--	4.3	3.4	
Energy	4.0	5.6	11.7	--	23.0
Industry Technology	--	10.1	6.7	66.7	
Agriculture	1.9	--	--	--	4.7
Health and Environment	14.9	5.6	10.5	--	2.1
General Scientific Purposes	3.8	26.3	48.6	--	63.8
Other	13.0	7.0	6.2	--	4.0

Source: Calculated from NSF and OECD Statistics and Research Report, Prime Minister's Office, Government of Japan.

Table 5. Distribution of Government R&D Expenditures Among Various Institutions

	U.S.A. (1981)	United Kingdom (1978)	W. Germany (1979)	France (1979)	Japan (1980)
Universities	19.6%	18.6%	37.4%	29.1%	45%
Government Research Institutes and Nonprofit Organizations	32.2	42.4	33.1	45.7	50
Industries	48.2	39.0	29.5	25.2	5

Source: The same as Table 4.

Table 6. Basic, Applied and Development Research in Various Countries

	U.S.A. (1977)	Great Britain (1975)	W. Germany (1975)	France (1977)	Japan (1979)
Universities					
Basic	58.5%	95.2%	100.0%	89.3%	57.7%
Applied	28.1	3.6	--	10.6	35.8
Development	13.3	1.3	--	0.1	6.5
Government Institutions and Nonprofit Organizations					
Basic	17.8	20.9	33.0	22.3	18.6
Applied	35.4	32.3		55.7	40.3
Development	48.8	46.8	67.0	22.0	41.1
Industries					
Basic	3.0	3.3	3.3	3.2	4.6
Applied	18.9	25.4		32.0	19.5
Development	78.1	71.2	96.7	64.8	75.9

Source: The same as Table 4.

Table 7. Overall Comparisons of Different Categories of R&D Expenditures

		U.S.A. (1979)	United Kindom (1977)	W. Germany (1975)	France (1977)	Japan (1979)
Basic	Total	12.7%	16.1	22.3	21.1	15.6
	Corp.	3.0	3.3	3.3	3.2	4.6
Applied	Total	23.0	25.4	77.7	34.4	25.9
	Corp.	18.9	25.4	96.7	32.0	19.5
Development	Total	64.3	58.5	Combined with Applied	44.5	58.5
	Corp.	78.1	71.2	Combined with Applied	64.3	75.9

Source: *White Paper*, Government of Japan, 1982.

Table 8. Shares of Research and Development Expenditures in Different Industries

Country Industry		Japan (1979)	U.S.A. (1977)
1.	Total	100	100
2.	Chemical	20.0%	11.3%
3.	Iron and steel	4.9	0.9
4.	Machinery	7.6	4.2
5.	Electric machinery	12.7	8.3
6.	Electronic and Communication machinery	15.6	21.8
7.	Automobile	15.3	14.1
8.	Aviation	--	24.4
9.	Precision machinery	3.2	4.9

Source: White Paper, Government of Japan, 1982.

Table 9a. Leading U.S. Firms in Company-Financed R&D Expenditure ($ million) 1980 (excluding Federal contracts)

Rank	R&D Expenditures	R&D as % of Sales
		%
1. General Motors	2224	3.9
2. Ford	1675	4.5
3. IBM	1520	5.8
4. American Telephone and Telegraph (AT&T) (incl. Bell and Western Electric)	1338	0.8
5. Boeing	767	8.1
6. General Electric	760	3.0
7. United Technologies	660	5.4
8. Eastman Kodak	520	5.3
9. International Telephone and Telegraph (ITT)	504	2.7
10. Exxon	489	0.5
11. DuPont	484	3.5
12. Xerox	434	5.3
13. Sperry Rand	337	6.2
14. Dow Chemical	314	3.0
15. Honeywell	295	6.0
16. Hewlett Packard	272	8.8
17. Minneapolis Mining and Manufacturing	283	4.6
18. Chrysler	278	3.0
19. Merck	234	8.6
20. Johnson and Johnson	233	4.8

Note: The exchange rate for the Yen in 1980 was 227 Yen per US Dollar.

Source: *Business Week*, 6 July 1981. (See Freeman [1982].)

Table 9b. Twenty Leading Japanese Firms in Expenditures on R&D in 1979[a]

Rank		Billion Yen	Ratio to Total Sales %
1.	Toyota Motor	104.0	3.7
2.	Hitachi	98.7	5.8
3.	Nissan Motor	90.0	3.3
4.	Toshiba	69.0	4.8
5.	Matsushita Electrical Ind.	50.0	2.9
6.	Nippon Eletric	43.0	6.0
6.	Mitsubishi Electric	43.0	4.0
8.	Mitsubishi Heavy Ind.	38.2	2.8
9.	Honda Motor	38.0	3.6
10.	Sony	32.8	7.0
11.	Fujitsu	30.5	6.1
12.	Nippon Steel	27.0	1.0
13.	Toyo Kogyo	20.5	2.5
14.	Nippondenso	20.5	4.5
15.	Takeda Pharmaceutical	20.1	4.8
16.	Fuji Photo Film	18.8	6.0
17.	Isuru	18.6	2.9
18.	Bridgestone	18.0	4.1
19.	Kobe Steel	17.7	1.7
20.	Tokyo Electric Power	15.2	0.7

[a] Financial year.

Source: Survey conducted by the Nihon Keizai Shimbun covered 1,170 firms of which 1,015 in manufacturing and 155 in non-manufacturing. (See Freeman [1982].)

II. A Model of the Technology Game and Intra-Industry Trade

1. Science-Related Innovations

Research and development is today a relatively integrated process. The national R&D effort can be viewed as a "science-based technological change" enterprise. Each country (or a typical firm in each country) engages in R&D activities to generate technological change in the form of "process innovations" and/or "product innovations". Each country competes in the world market with the best innovations available. The success of intra-industry trade crucially hinges on the success of R&D investment in each country.

The process of science-related technological innovation can be conceived of as a process of creating (or producing) stocks of basic (fundamental) and applied (practical) knowledge that serve as inputs in the generation of new technologies, some of which are more productive than old technologies and therefore eventually displace the old technologies via adoption by profit-maximizing firms. The entire process is schematized in Figure 2.

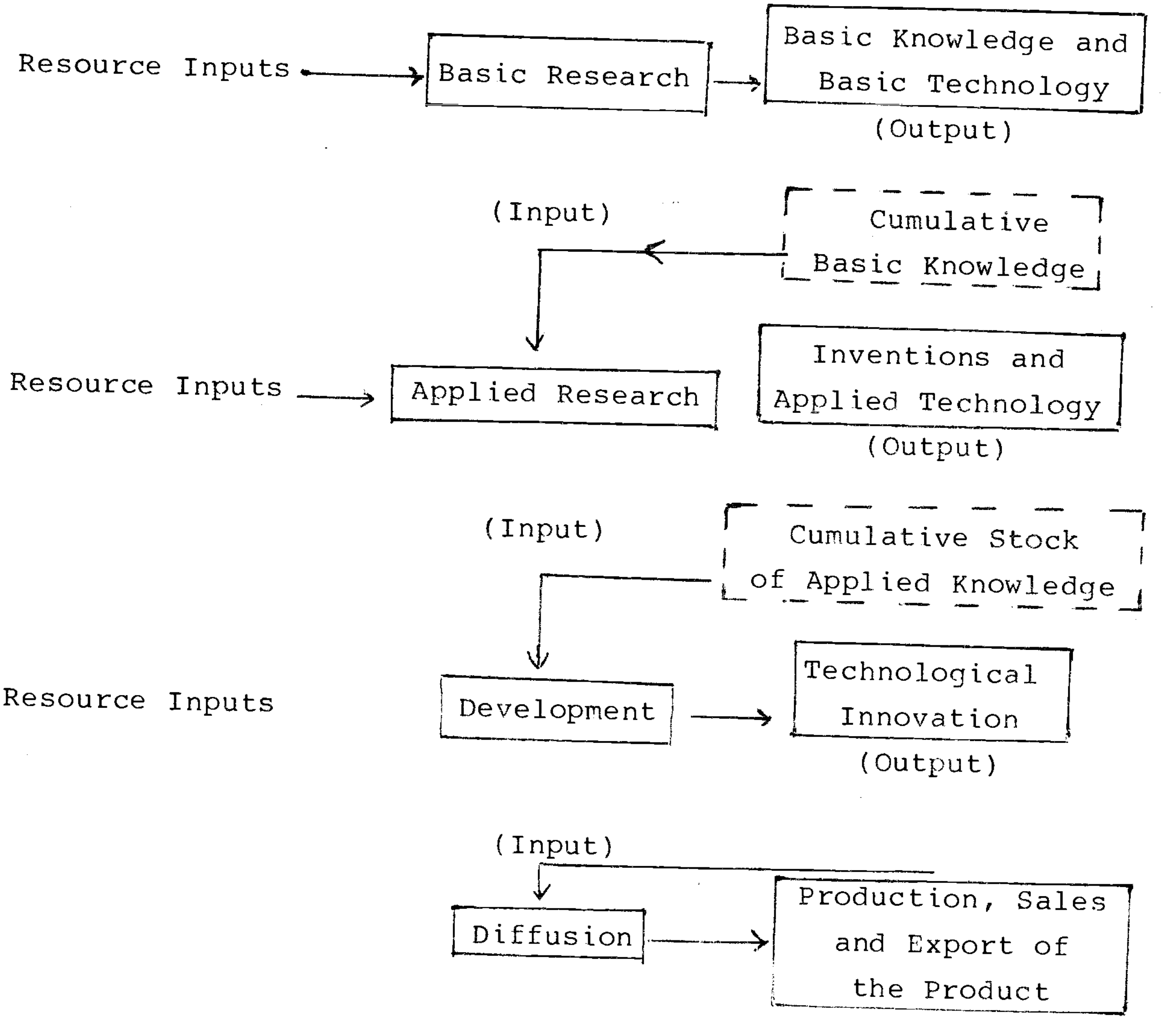

Figure 2

Science-Related Innovations

Essentially, the transformation of scientifically derived kowledge to more productive technologies is a dynamic process. First, specialized resources, such as skilled labor (scientists and laboratory technicians) and specialized capital (laboratory apparatus), are used to generate basic, or fundamental, knowledge. This new knowledge constitutes an addition to the stock of basic ideas and insights regarding physical and human nature. The stock of basic knowledge and basic technology then serves as an essential input in the endeavor to produce new practical ideas or inventions. A good example of the role of basic knowledge in the systematic process of generating practical ideas is the development of the transistor by the American Telephone and Telegraph Company's Bell Laboratories (see Nelson [1962]). The production of new inventions also requires the use of specialized factors of production. The stock of applied knowledge in turn serves as an important input in the next stage, the development stage, in which innovative products or production technologies are readied for commercial applications (i.e., market-tested). If the new products demonstrate consumer acceptance and if new technologies prove to be more cost effective than existing technologies, a diffusion stage occurs. Least costly production technologies eventually displace older technologies, and successful new products are imitated by firms which are not the innovators. Thus, either by "output-augmentation" or "factor-augmentation" (factor-saving technical progress), the process of science-related technological progress implies higher productivity, higher profits and larger market share of the internationally competing firm.

Although most economists would agree that there is a cause-and-effect (substantive) relationship between R&D and profit gains, there is no universal agreement regarding the extent of the relationship. One reason for this is the fact that there is no temporal stability to the various stages of science-related technological innovations. In some cases, a stream of past R&D expenditures (use of specialized resources for the production of basic and applied technologies) could lead to relatively rapid observed improvements in profits and market shares, whereas in others the reverse is true.[1] In other words, lags tend to be variable. Second, there is a great deal of uncertainty associated with the production of new basic and applied knowledge. The "production" relationship between scientific and engineering inputs and the output of new knowledge is not a deterministic one. New knowledge may be the outcome, but there is no way to be assured that it will be. Essentially, most R&D endeavors deal with the unknown, i.e., represent an "exploration" of the unknown. Thus, uncertainty of outcome and the variable lag between inputs and outcomes make it extremely difficult to verify the relationship between R&D and gains in profit and the market share.

Nonetheless, it is useful to idealize that an important dimension of technological innovation is that it is the outcome of investment-type activities. For example, the firm reinvests a fraction of present profit in R&D for the purpose of enjoying future cost-saving benefits via improvements in the efficiency of its production technology. As long as R&D investments produces a higher rate of return (adjusting for differences in risk) than other forms of investment, the firm's investment resources will tend to flow into R&D-type activities. The process of technological innovations should be studied within the context of the efficient allocation of limited resources under institutional, technological and market constraints. Technological innovations may be regarded as "endogenous" change generated by the motives of long-run profit maximization and market control.[2]

Studies done by industrial organization specialists have shown that the R&D cost relation to output follows the same (U-shaped) pattern as the cost relation of other commodities. Average cost curves of R&D tend first to decline with respect to output, but later they either start rising or stay at the same level. This pattern indicates that R&D research can be viewed as one of the factors of production, and that the production function approach may be applied to the theory of technological innovation.

2. Innovations and Profit Maximization

The ideas presented in the previous section can be formalized. We assume that certain levels of the (same) basic and applied knowledge are needed to produce an output regardless of the location of the firms. For instance, to produce automobiles in the U.S.A. or in Japan, certain levels of the (same) basic and applied knowledge are needed--how gasoline engines work (basic knowledge) and how workers and managements need to cooperate to produce automobiles (applied knowledge). The problem to be analyzed here is the matter of how new flow of basic and applied knowledge (technology) can be generated by companies in the two countries so as to enable the firms to compete in the world automobile market.

There are two main categories of research: basic and applied. We include development efforts under the "applied" category. The process of accumulation of knowledge and development of new technology is endogenous. The firm may alter its stocks of basic knowledge and applied (technical) knowledge by producing flows of the two types of knowledge via basic and applied research. Hence, the firm may alter the levels of basic and applied technologies by appropriate (optimal) allocation of research and development expenditures. Basic knowledge is considered to be an "intermediate product" in the production of new applied technology.

In the production of a given product, we assume that there are two countries (or two monopolistic firms, one in each country). Country I's firm engages in the full-range of research and development, full-range in the sense that both basic and applied research is done, while Country II's firms concentrates on applied research with the importation of basic technology developed in Country I.

Country I's R&D Activities

Let $A^1(t)$ and $B^1(t)$ be respectively the stocks of applied and basic knowledge at time t for the firm in Country I. The production (flow) of basic and applied knowledge is subjected to the following "dynamic" innovation functions:

(1a) $$B^{1} = f(a'_{B}, b'_{B}) - \mu B^{1}$$

(1b) $$A^{1} = h(a'_{A}, b'_{A}, B')A^{1} - \upsilon A^{1},$$

where $\mu > 0$ is the rate of depreciation in basic knowledge and $v > 0$ is the rate of depreciation in applied knowledge. The depreciation factor takes into account the fact that a part of the effort to produce knowledge is aimed at renewing and transferring knowledge. An increase in the stocks of basic and applied knowledge depends on the "innovation" functions, f and h. Thus, the rate of change (flow) of basic knowledge $(\frac{dB^{1}}{dt} = B^{1}(t))$ is positively related to the specialized research workers, a'_{B}, employed to produce basic research, and to the research capital b'_{B}, but that rate is negatively related to the depreciation rate μ. In the same way the rate of change (flow) of applied knowledge $(\frac{dA^{1}}{dt} = A^{1}(t))$ depends on the specialized workers, a'_{A}, and research capital b'_{A}. It is assumed here that the "innovation" functions satisfy the concavity and other regularity conditions. It was argued earlier that the "innovation" production functions are usually not deterministic functions. Thus, there exists technical uncertainty with respect to outcome. For simplicity, and also for mathematical reasons, we ignored technical uncertainty inherent in the production process of basic and applied knowledge.

"Innovation" functions represented by (1a) and (1b) do not fully take into account the delayed or lag effects of basic and applied research on new innovations. There are significant time lapses in the process of the transformation of basic knowledge into applied knowledge and of applied knowledge into practical innovations. Examples of this "gestation period" are numerous. For instance, the theory of relativity antedated the development of nuclear fission by almost forty years. The application of calculus to most problems in the physical and social sciences did not occur until long after the days of Newton and Leibnitz.[3]

In the "innovation" functions (1a) and (1b) the assimilation of basic knowledge is reflected only by the partial derivatives term $\frac{\partial h}{\partial B}$. This partial derivative term represents the impact of the current changes in the stock of basic knowledge on the rate of change of applied knowledge. The faster current additions to the stock of basic knowledge are transformed into new applied knowledge--i.e., the faster the rate of assimilation--the higher the value of the partial derivative. This depiction of the relationship between basic knowledge and applied knowledge is incomplete. In fact, the generation of new applied knowledge is a function not only of current additions (net investment) of basic knowledge, but also of past additions of basic knowledge. Figure 3 depicts the probable cumulative effects of investment in research and development on new technology. The results of past investments appear continuously, with the investment of, say, five years ago yielding the greatest effect. The form and shape of this curve depend on the particular research project the firm engages in. Various weighting functions are appropriate.[4]

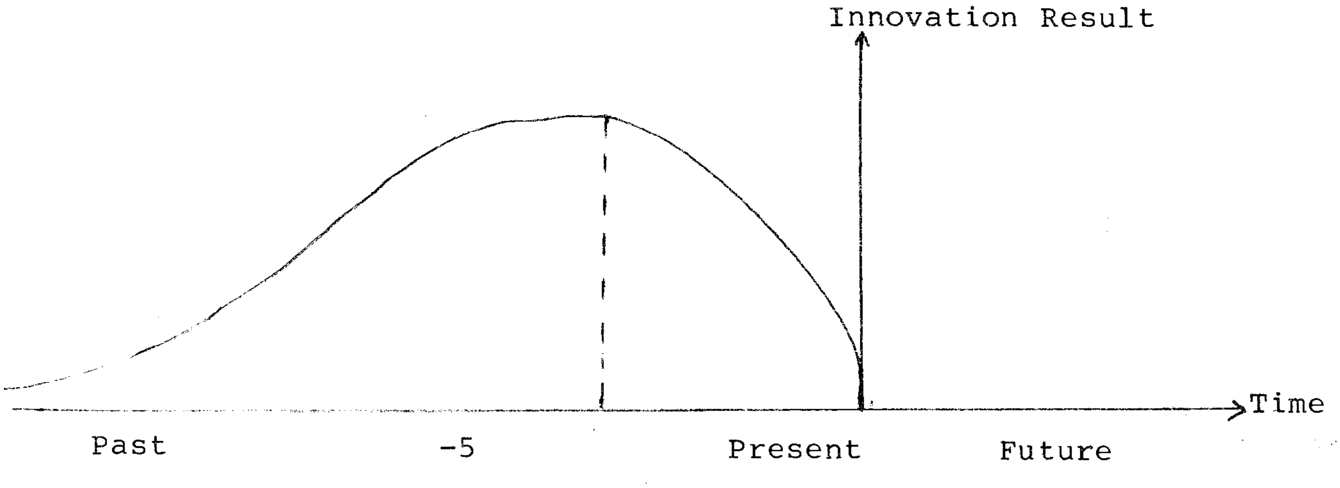

Figure 3

Profile of Innovation Outcomes

The cumulative effects of research investment are defined by:

$$\text{Flow of New Technology at } t = \sum_{\tau=-\infty}^{t} \text{Past Research-Investment Effects at } \tau.$$

By writing the past research investment effects as the weighted product of the potential technological progress function and the time-delay (weighting) function, and by substituting for the discrete summation $\sum$, the continuous summation (integration), we formally express the actual flow of both basic and applied knowledge as:

$$\text{(2a)} \qquad B^1(t) = \int_{-\infty}^{t} f[a_B'(\tau), b_B'(\tau)] W_B'(t-\tau) d\tau - \mu B^1(t)$$

$$\text{(2b)} \qquad A^1(t) = \int_{-\infty}^{t} h[a_A'(\tau), b_A'(\tau), B^1(\tau)] A^1(\tau) W_A^1(t-\tau) d\tau - \upsilon A^1(t).$$

The weighting functions W_A' and W_B' usually satisfy the property

$$\int_{-\infty}^{t} W_i'(t-\tau) d\tau = 1, \qquad i = A, B.$$

Then equation (2a) or (2b) states that the realized gross increase in technical knowledge is a weighted average of past values of potential gross increase in basic knowledge. These equations simply show that it takes time to develop new technology and new innovation.

R&D Activities in Country II

Let $A^2(t)$ and $B^2(t)$ be the stocks of applied and basic knowledge at time t for the firm in Country II. Here we make the crucial assumption that Country II does not engage in basic research, or at least engages in very little basic research. The firm in Country II acquires basic knowledge from the firm in Country I. Assume that the flow of basic knowledge in Country II is proportional to the flow of basic knowledge produced in Country I.

(3a) $B^2 = \gamma B^1, \quad 0 \leqslant \gamma \leqslant 1,$

where γ is the proportionality coefficient which in turn depends on the amount of money paid as royalty and licensing fees, etc. In general, γ is not constant, but varies depending upon the nature of the agreement between the firms in the two countries. The index γ may be looked upon as the index of diffusion of basic knowledge. When $\gamma = 0$, we have the case of technology embargo, while $\gamma = 1$, the case of perfect dissemination of basic knowledge. In general, we assume that

(3b) γ = a function of cost of acquiring B_1.

If the flow of basic knowledge in Country I is of an academic and very fundamental nature, the cost of acquiring it may be minimal. For example, the costs of technical and academic journals may be all that Country I has to pay. Information regarding some basic knowledge may be obtained simply by purchasing the product which manifests such information. In extreme cases, the flow of basic knowledge in Country I may be obtained through illegal practices such as industrial espionage. Also the main supply of the flow of basic knowledge may be provided by the foreign-study system of employees and trainees of the foreign firm. Using (3a) and (3b) we have

(4a) $B^2 = \gamma \text{ (cost of acquiring } B^1) \quad B^1.$

The flow of applied knowledge in Country II is generated from the same type of innovation function as Country I's, because Country II is producing the identical (or very slightly different) product as Country I. Hence, we present

$$(4b) \qquad A^2(t) = \int_{-\infty}^{t} \delta h(a_A^2(\tau), b_A^2(\tau), B^2(\tau))A^2(\tau)W_A^2(t-\tau)d\tau - \nu A^2(t)$$

where a_A^2 = specialized workers in Country II in production of applied technology, b_A^2 = capital used in producing the flow of applied knowledge and W_A^2 is the weighting function representing cumulative delayed or lag effects of R&D investment. The technical progress function in Country II, is in general different from that in Country I. To simplify the analysis, we have assumed

$$(4c) \qquad h^2 = \delta h^1 = \delta h, \ \delta = \text{constant} > 0.$$

If δ is greater than unity, Country II is more efficient in producing the flow of applied knowledge, while if it is less than unity, Country II is less efficient than Country I. We also assume that $W_A^1 = W_A^2$. Using (4c) we write the technical progress function for applied innovation as

$$(4d) \qquad A^2(t) = \delta \int_{-\infty}^{t} h(a_A^2(\tau), b_A^2(\tau), B^2(\tau))A^2(\tau)W_A^1(t-\tau)d\tau - \nu A^2(t).$$

$$\delta = \text{constant} > 0.$$

In addition, if the diffusion index of basic technology γ is constant, then $B^2(t) = \gamma B^1(t)$ and production of applied technology can be shown by

$$(4e) \qquad A^2(t) = \delta \int_{-\infty}^{t} h(a_A^2(\tau), b_A^2(\tau), \gamma B^1(\tau))A^2(\tau)W_A^1(t-\tau)d\tau - \nu A^2(t).$$

Essentiality of Basic Knowledge

The main feature of applied technology is that basic knowledge is assumed to be essential for the production of applied knowledge. Looking at the extreme case in which the stock of basic knowledge is zero, we would find that production of applied knowledge is impossible. For instance, if in equation (4e) the diffusion index γ is zero--complete shut off of technology transfer--then the flow of applied innovation ceases to exist, i.e.,

(5a) $$h(a_A, b_A, 0) = 0$$

(5b) $$\frac{\partial h}{\partial B}(a_A, b_A, 0) = +\infty.$$

The first expression states that without basic knowledge the production of applied knowledge is impossible. The assumption is quite realistic. Elementary language and numerical skills fall under the category of basic knowledge. A researcher who has no basic knowledge of a certain computer language could not possibly produce useful programs written in that language. The second expression states that the marginal productivity of the first unit of basic knowledge in the production of applied knowledge is extremely large. As an approximation, one may envision the change in applied knowledge that is brought about by mastering simple arithmetic. Basic knowledge itself is not worthwhile in the sense that it will be directly applied to produce output, but is essential to the production of applied knowledge which directly helps to produce output in a more efficient manner.

3. Technology Game

The firm in each country produces the identical (or slightly differentiated) product $Y(t)$ with the aid of factor inputs in each country and sells it in the world market at the price of $P(t)$. The world market demand function is given by

(6a) $$P[t, Y^*(t)] = P[t, Y^1(t) + Y^2(t)],$$

where Y^* = the world production of $Y(t) = Y^1 + Y^2$ and Y^i, $(i = 1,2)$, are the quantities of Y produced by Country I and Country II respectively. The independent variable t in P represents the exogenous factors affecting the demand function.

The cost function for each firm is given by

$$C^i = \frac{G(w^i(t), r^i(t))Y^i(t)}{A^i(t)}, \quad i = 1,2. \tag{7a}$$

Here we implicitly assume that the production function of output Y^i is of the constant-return-to-scale type and that each firm engages in cost-reducing process innovation with the stock of applied knowledge, i.e., an increase in A^i will proportionately decrease the cost of producing Y^i. In equation (7a) $w^i(t)$ and $r^i(t)$ represent respectively the wage rate and the return to capital in each country, $i = 1,2$.

Each firm's objective is to choose the appropriate amounts of output Y^i and appropriate flows of basic and applied knowledge in such a way that the long-run profit is maximum. One extreme case would be that the firm makes no additional investment in the creation of technical progress but produces only output Y^i. Generally, this policy is not optimal, because by investment in basic and applied knowledge, each firm will further reduce the cost of producing output Y^i. As long as the savings in cost exceed the revenue increases due to the production of more Y^i, the firm will invest in technical progress ventures. This trade-off relationship can be more precisely studied after we specify the rules of the dynamic game engaged by the firms in Country I and Country II.

Cournot-Nash Dynamic Game

Each firm in the two countries allocates resources under perfect information in that each firm knows the values of all current (state) variables of basic and applied knowledge. Each firm chooses the time paths of the output and resources according to either a closed or open loop control strategy.[5] We assume that the technology game which the two firms in the two countries play is a Cournot-Nash differential game with either a closed or open loop control strategy.

Closed vs. Open Loop Strategies

What really makes the difference between the open and closed strategies depends on the assumption of the structure of information available to the firms at every instant of time. The closed loop strategy takes into account:

(a) Information on a firm's own actual performance at every point in time.

(b) Information on his rival's strategies and the current value of the state variables, i.e., basic and applied knowledge variables.

On the other hand, for the open-loop strategies, the firms totally ignore the above mentioned information. Thus, in general, the closed-loop strategy is more realistic and more attractive, because it takes account of all available information useful for decision making--the structure of perfect information pattern (Basar and Olsder [1982]). In many cases, however, it may still be appropriate to assume that each firm adopts an open-loop control strategy of imperfect information structure because:

(a) the cost of getting more information is not negligible,

and

(b) even if there is no such direct cost, technically it may be very complicated for the firms to correctly estimate the value of the current state.

Price Expectation Hypotheses

In making decisions about the choice of physical output and research outputs, each firm must know the future course of the price of output Y^i, and input prices in each country. Here, we assume that the firm's vision for the future course of those prices is based on the so-called rational expectations hypotheses. More specifically, we assume that the commodity price and the factor input prices increase at certain constant rates:

$$\text{(6b)} \qquad P[t,Y^*(t)] = e^{\alpha t}\bar{P}[Y^*(t)], \; Y^* = Y^1 + Y^2$$

$$r^i(t) = e^{\beta_i t}\,\bar{r}^i \tag{8a}$$

$$w^i(t) = e^{\beta_i t}\,\bar{w}^i \qquad \bar{P} > 0,\ \bar{r}^i > 0 \tag{8b}$$

$$\bar{w}^i > 0,\ \bar{P}_{a^i} > 0$$

$$P_{a^i}(t) = e^{\alpha t}\,\bar{P}_{a^i} \qquad \bar{P}_{b^i} > 0 \tag{8c}$$

$$P_{b^i}(t) = e^{\alpha t}\,\bar{P}_{b^i} \qquad i = 1,2. \tag{9d}$$

We assume that the commodity price $P(Y^*)$ is increasing at the same rate, α, as the prices of inputs in the R&D sector in each country, whereas the wage rate and the return to capital both grow at rate β_i. These assumptions will ensure the existence of a long-run Cournot-Nash equilibrium. We also assume that the social discount rate in each country is the same and equal to σ and that output price is increasing as fast as the input prices of research factors, but it does not exceed the social discount rate, whereas the input prices of regular factors increase faster than or as fast as the output price (because of technical progress), i.e.,

$$\sigma \geqq \beta_i \geqq \alpha \geqq 0. \tag{9}$$

Using these assumptions, we now consider the technical progress index in real (net) terms. Let $g(t)$ be defined by

$$g^i(t) = \frac{A^i}{e^{(\beta_i - \alpha)t}} \qquad i = 1,2. \tag{10}$$

The term $g^i(t)$ measures the real effect of technical change in applied technology.

Cost Sharing of Basic Research

Earlier in discussing the diffusion process of basic knowledge, we assumed that Country II does not engage in basic research, but pays a certain amount of royalties and licensing fees to Country I. Let us assume that the two firms have a long-term agreement to share the cost of developing basic technology. Let us assume that θ% of the annual cost of developing basic technology is financed by the firm in Country II. Hence, the cost of acquiring B^1 in the second country is equal to

(11) cost of acquiring B_1 in Country II at t = θ × cost of producing B^1 in Country I at t.

Under these assumption we now present the technology game. To keep the notation simple, the subscripts "t" and "τ" will be suppressed from the equations. The firm in Country I tries to maximize

(12a) Long-run Net Profit = Revenue - Production Cost
- Applied Research Cost
- $(1-\theta)$ × Basic Research Cost,

while the firm in Country II tries to maximize

(12b) Long-run Net Profit = Revenue - Production Cost
- Applied Research Cost
- θ × Basic Research Cost,

subject to the dynamic constraints of the "innovation" functions and the predetermined game rules.

More formally for Country I's firm:

(13a)
$$\underset{\substack{a_A^1, a_B^1 \\ b_A^1, b_B^1, Y^1}}{\mathrm{Max}} \int_0^\infty e^{-\rho t}[P(Y^*)Y^1 - \frac{Y^1}{g^1} - (\overline{P}_{a^1} a_A^1 + \overline{P}_{b^1} b_A^1) - (1-\theta)(\overline{P}_{a'} a_B' + \overline{P}_{b'} b_B')]dt$$

subject to the technological constraints,

(13b)
$$g^1 = - \eta g^1 + \int_{-\infty}^{t} e^{-\varepsilon_1 (t-\tau)} g^1 h(a_A', b_A', B') W_A'(t-\tau) d\tau,$$

(13c)
$$B^1 = - \mu B^1 + \int_{-\infty}^{t} f(a_B', b_B') W_B'(t-\tau) d\tau$$

$$\eta_1 = \beta_1 - \alpha + \nu, \quad \varepsilon_1 = \beta_1 - \alpha, \quad \rho = \sigma - \alpha,$$

given the optimal paths of the variables determined by the firm in Country II. For Country II's:

(14a)
$$\underset{\substack{a_A^2, a_B^2 \\ b_A^2, b_B^2, Y^2}}{\mathrm{Max}} \int_0^\infty e^{-\rho t}[P(Y^*)Y^2 - \frac{Y^2}{g^2} - (\overline{P}_{a^2} a_A^2 + \overline{P}_{b^2} b_A^2) - \theta(\overline{P}_{a^1} a_B^1 + \overline{P}_{b^1} b_B^1)]dt$$

subject to the technological constraints

(14b)
$$g^2 = - \eta_2 g^2 + \delta \int_{-\infty}^{t} e^{-\varepsilon_2 (t-\tau)} g^2 h(a_A^2, b_A^2, B^2) W_A^1(t-\tau) d\tau$$

(14c)
$$B^2 = \gamma[\theta(\overline{P}_{a^1} a_B^1 + \overline{P}_{b^1} b_B^1)] B^1$$

$$\eta_2 = \beta_2 - \alpha, \quad \varepsilon_2 = \beta_2 - \alpha, \quad \rho = \sigma - \alpha,$$

given the optimal paths of the variables determined by the firm in Country I.[6]

It should be noted that there are basically three crucial parameters in this differential game: δ = relative efficiency parameter for applied technology, γ = diffusion index of basic technology and θ = the index of cost sharing of basic research. Their relative magnitudes will determine how the market evolves in the long run.

4. Technological Competition and Market Shares

A simplified version of the above mentioned dynamic game is solved in the appendix of this paper. Although the conclusions which follow may not be universally true, they provide some useful insights regarding the technology game taking place in the real world. First, the results presented here are "local" results in that the simplification of the general model is made by assuming the linearity of the world demand function and quadratic cost functions. The main result is that the final market performance depends on the types of strategies which the two firms employ. The closed-loop strategy yields the most interesting results. For instance, the firm with relative efficiency in applied technology does not necessarily control the market, even though the cost of sharing expenditures on basic research is very small. This is certainly a paradox. For instance, this implies that even though the Japanese firms have advantages in producing output because of relative efficiency of applied research and/or essentially free inflow of basic technology, they need not necessarily control the world market.

Closed-Loop Strategy

The relative market shares depend on how efficient each country (firm) is in applied technology. Thus, if the relative (real) efficiencies are identical $g^1 \equiv g^2$, the market shares are identical $Y^1 \equiv Y^2$. In general, we have

(15a) $$Y^1 \gtrless Y^2,$$

corresponding to

(15b) $$g^1 \gtrless g^2.$$

The relationship between the index of relative efficiency of applied research δ and the index of diffusion of basic research γ in the steady state is summarized in Figure 4. The curve AB is an iso-share curve on which the world market is equally divided by the firms in the two countries. Any point above this line shows that Country I's firm controls the market with $Y^1 > Y^2$, while any point below that line indicates that Country II's firm controls the market with $Y^2 > Y^1$. The iso-share curve is a monotonically increasing function of the diffusion index γ, which implies that as the level of diffusion of basic knowledge rises, it is more likely that the second country's firm can control the market, even though its firm is relatively inefficient in applied technology compared with the first country's firm. This point is illustrated by Q_2 in Figure 4. On the other hand, if the diffusion index is small, the relatively efficient applied technology in Country II is not enough to overcome the lack of essential basic technology. This is illustrated by the point Q_1.

Next, what will happen if the index of cost sharing of basic technology changes? Figure 5 shows that an increase in the cost sharing of basic technology by Country II will shift the iso-share curve downward. This is reasonable because by paying more royalties to Country I, Country II looses the competitive edge in production and trade. The extreme case of $\theta = 1$ will result in the absolute control by Country I when the iso-share curve coincides with the horizontal axes. The other extreme case of $\theta = 0$ will result in the total loss of the market by Country II, or the absolute monopoly by Country I.

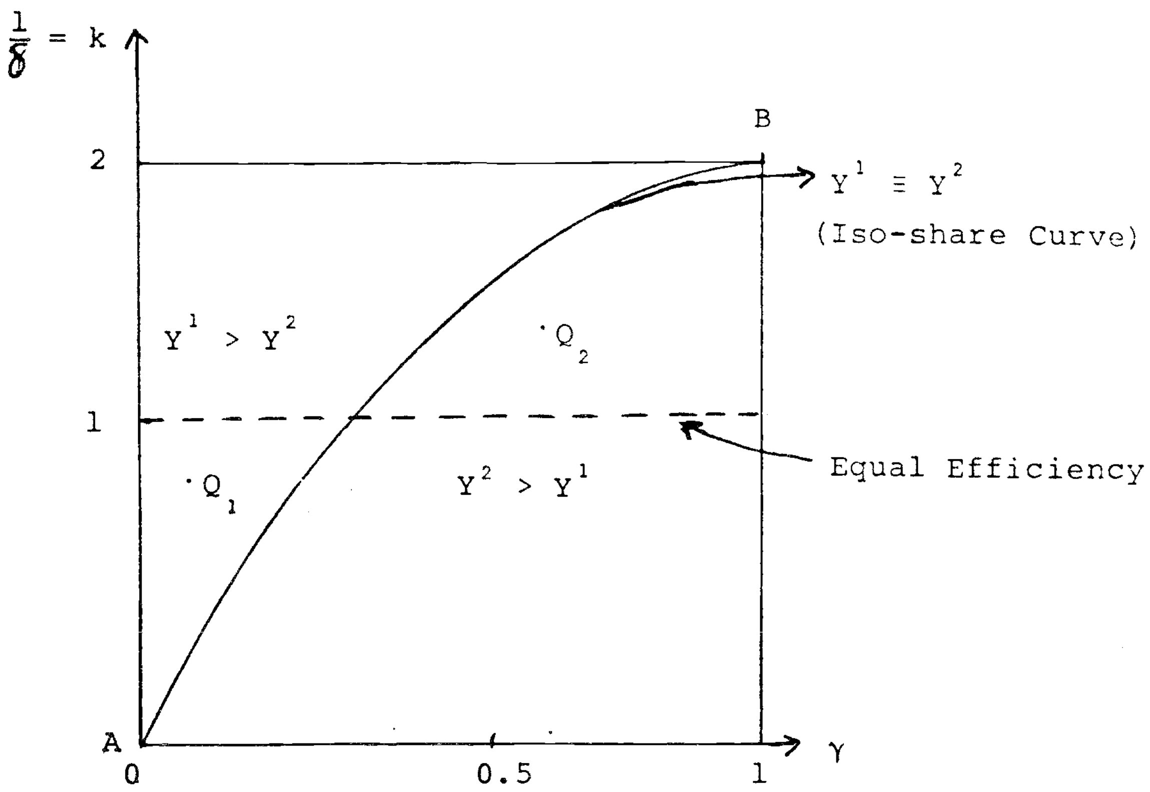

Figure 4. Market Share and Competition

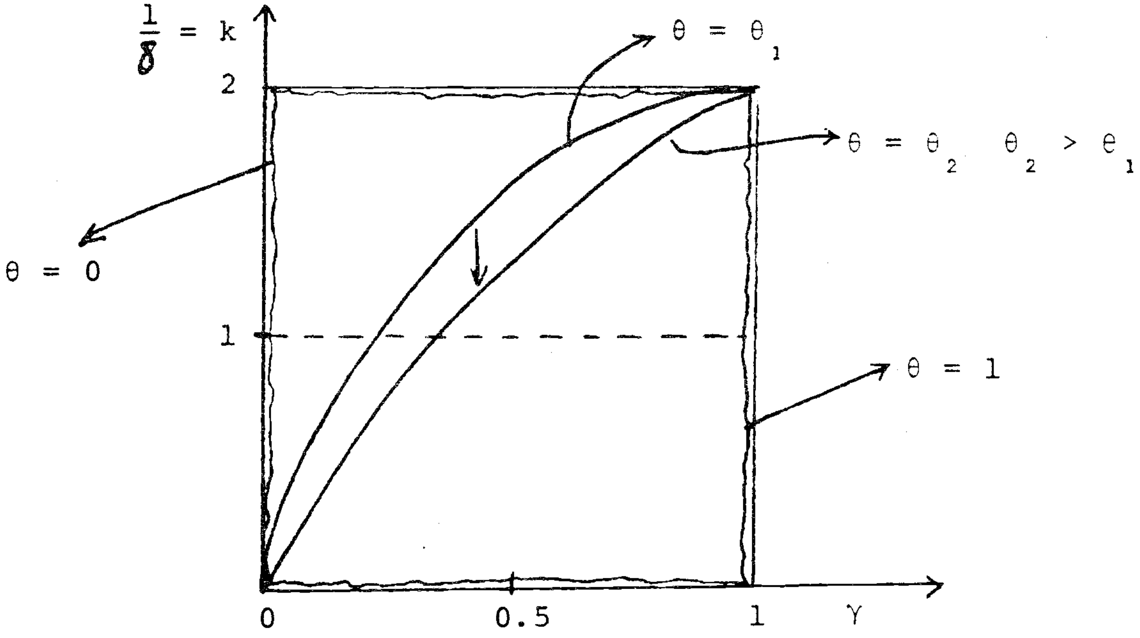

Figure 5. Effect of Changes in Cost Sharing of Basic Technology

Open-Loop Strategy

When the firms do not completely utilize all available information, as in the case of open-loop strategies, the results are quite different. As shown in Figure 6, the iso-share curve always approaches to the point where $\delta = 1$, the equal-efficiency point. Hence, there is no possibility that the inefficient firm in applied technology can control the market. It is more likely that Country I's firm will control the market by restricting the diffusion index to a lower value.

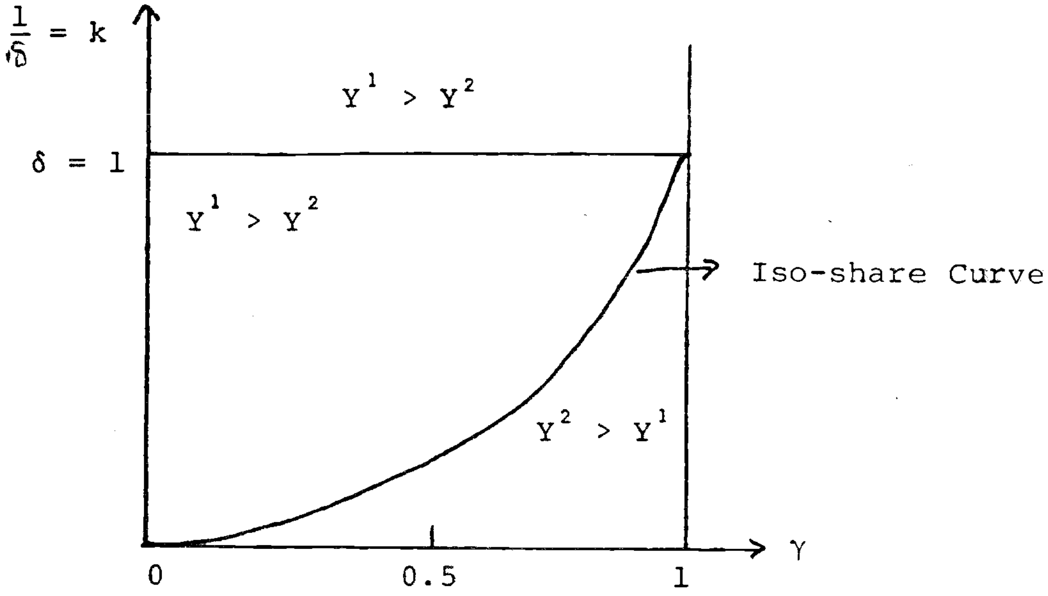

Figure 6. Open-Loop Strategy and the Share of the Market

Next, consider a point like Q_2 in Figure 4 where, under the closed-loop strategy, Y^2 is greater than Y^1. Under the structure of information based on the open-loop strategy, this point always represents the situation $Y^1 > Y^2$. Hence, under the open-loop strategy Country II will never be able to control the market unless they have relatively efficient applied technology. Another way of looking at this point Q_2 under the different strategies is that under the structure of closed-loop perfect information pattern, the country which does not engage in the production of basic knowledge can still control the market by taking advantage of information efficiency. The abundance of information helps a country even though it is relatively inefficient in production of applied technology.

The analysis presented here by no means covers all possible outcomes of the technology game which two countries can engage in, however, it does represent some aspects of the real world. The country with relatively efficient technology and information structure can overcome diffusion handicaps, while the country with relatively inefficient applied technology can also control the market by restricting the information and/or by forcing the other country to share the cost of basic technology.

Mathematical Appendix

The technology game presented in the paper is solved for a special, but very important case. For simplicity: (1) We assume that either one of the factor inputs of specialized and professional categories in the two countries a_j^i, b_j^i $(i = 1,2,$ and $j = A,B)$, say b_j^i is assumed to be fixed so that in each country the control variables are reduced to a_A^i, b_B^i and Y^i. (2) Explicit solutions are given in the neighborhood of the steady-state equilibrium. Hence, the relevant functions are reduced to either quadratic or linear functions. (3) Also in view of the Sato-Nôno theorem (see Sato [1981], Sato and Nôno [1982]), the integro-differential equations for the technical progress functions are reduced to the ordinary differential equations with appropriate weights. (4) Finally, the model is reduced to the simplified form by introducing the concept of the "effective marginal costs" $C^i = \frac{1}{g^i}$ and by changing the control variables to Y^i and to the true derivatives of the marginal costs and of the basic technology, i.e., $\dot{C}^i$ and $\dot{B}^i$. Hence, the model which has been explicitly worked out is expressed by the system of the Hamiltonian functions for the two countries:

$$(A\text{-}1) \qquad H^1 = P(Y^*)Y^1 - C^1Y^1 - S(C^1,B^1,U^1) - (1-\theta)T(B^1,V^1) + \lambda_1^1U^1 + \lambda_2^1U^2 + \pi^1V^1,$$

$$(A\text{-}2) \qquad H^2 = P(Y^*)Y^2 - C^2Y^2 - \frac{1}{\delta}S(C^2,\gamma B^1,U^2) - \theta T(B^1,V^1) + \lambda_1^2U^1 + \lambda_2^2U^2 + \pi^2V^2$$

where $U^1 = \dot{C}^1$, $V^1 = \dot{B}^1$, $U^2 = \dot{C}^2$ and $V^2 = \dot{B}^2 = \gamma\dot{B}^1$. Also S and T are the cost functions of applied technology and basic technology expressed by the quadratic forms. And finally λ_j^i and π^i are the shadow prices of the control variables. The discussions in the paper is based on the above model with the three explicit parameters δ, γ, and θ.

FOOTNOTES

[1] For a more extensive discussion of the relationship between scientific knowledge and its practical applications, refer to Carter and Williams [1957].

[2] For the discussion of the aspect of relationship between R&D and productivity gains, refer to Sato and Suzawa [1983].

[3] The delayed or lag effect is in technological development is known as "dynamic Böhm-Bawerk" effect in the recent literature (see Sato and Suzawa [1983]).

[4] Various forms of lag effects are considered in Sato and Suzawa [1983, pp. 85-89].

[5] The mathematical implications of a Cournot-Nash dynamic differential game under different strategies are discussed in detail in Sato and Tsutsui [1983, 1984].

[6] For simplicity we normalized the initial values of $\bar{r}^i$ and $\bar{w}^i$ to unity, and thus, production cost in each country is simply equal to $\frac{Y^i}{g^i}$.

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