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The cutting edge of international technological competition

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Abstract

Markets for the products of high-technology industries are usually imperfectly competitive, providing a rationale for profit-sharing strategic trade policies. But such measures must be in place before the identity of the successful firm is known. Therefore they will attract some firms who then fail. To evaluate the net effect of R&D promotion policies, the model allows free entry of identical firms in each of two countries. It is found that if country A's government gives its firms the slightest cost edge in conducting R&D, country B's R&D sector is totally wiped out. However, this domination reduces aggregate welfare in A. This country can instead benefit at B's expense by instituting policies that damage B's R&D prospects.

1. Introduction

Activities at the frontier of technology occupy a special place in public policy. Countries aim to achieve, preserve, or regain world leadership in such industries, often at great cost and sometimes when there is little chance of success. Economists criticize many of the arguments commonly advanced for government support for research and development, or of high-technology industries more generally. they point out that causes of national prestige and security can be hijacked by special interests. but economists do recognise some legitimate reasons for not leaving R&D to the mercies of the market. There are two broad classes of economic problems that can justify government support for

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high-technology industries. The first concerns positive externalities or spillover benefits generated by R&D. The second is that markets for products at the forefront of technology are by their nature imperfectly competitive, and allow pure profits. In this paper I shall concentrate on the profit aspect; for perceptive remarks on external economies, see Spence (1984) and Krugman (1984, p. 136–40; 1987, §II).

When international competition allows pure profit, it is in each country's interest to capture it. When the government has better strategic instruments for this than do firms, there is a case for policy intervention. This insight, developed in a number of papers by Brander and Spencer, is illustrated for the case of R&D in Spencer and Brander (1983). A dynamic extension is in Cheng (1984). These papers consider a two-stage duopoly with one firm in each country. Each can commit itself to a larger R&D expenditure at stage 1. This will give it a lower unit cost of production, and the prospect of a larger profit in the Cournot competition at stage 2.

These models neglect the uncertainty that is present in most high-technology R&D. The effort may fail, or a rival may succeed before one's own research comes to fruition. I shall argue that issues of market structure and public policy are importantly altered by the recognition of such uncertainty, and shall illustrate the implications for international competition using a simple and familiar model of an R&D race.

My starting point is the observation that, when success cannot be predicted with certainty, prospective entrants to the R&D competition as well as policy-makers judging the performance of the industry must take an *ex ante* viewpoint. A firm must look at its expected profit, calculating the probabilities and the consequences of success or failure. A government must recognize that some firms will succeed and others will fail, and consider only the net profit of the whole industry as contributing to GNP. This alters the scope of different kinds of policies in different, but ultimately equivalent ways.

Of the policies listed above, most are anonymous: they establish a framework of taxes or subsidies, patent laws, trade practices, etc., and these are available to all firms. Indeed, it is doubtful if the U.S. constitution and politics could allow the exercise of selectivity to make the benefits of R&D policies available only to a chosen set of firms. In response to the announced policies, entry will occur until the expected profit to an additional entrant becomes negative. In the case of a large group of identical entrants, the industry as a whole will have zero expected profit, and the profit-capture motive for policy will disappear.

Other countries like Japan may sometimes successfully restrict entry, but one suspects that even they are subject to similar political pressure from the firms they seek to exclude. In any event, unless they can pick winners *ex ante* and exclude all losers, they can only achieve a target probability of winning by allowing enough firms most of whom will be *ex post* losers. This will have a similar effect on the industry profit.

In any sensible model of R&D competition, the expected profit of each firm will be an eventually declining function of the number of entrants to the race. The free-entry equilibrium will occur where this function crosses zero. A government that seeks greater profit for this industry can only do so by admitting fewer firms, whether by direct restriction or by tax policies. On the other side of the coin, a larger number of firms can only be achieved at a social cost in the form of negative industry profit. In international competition, this says that policies to achieve dominance by supporting one's own firms can lower national welfare. There is some scope for one country to gain by actively harming other countries' R&D prospects, but such directly predatory policies run great risks of mutually damaging retaliation.

The particular model I use in making these points has an incidental feature of some independent interest. When there is free entry in both countries, I find that the slightest advantage to the firms of one country in the innovation race will completely eliminate R&D in the other country, that is, none of its firms will enter. The intuition behind the result is that, in the appropriate sense, the process of R&D has a U-shaped average cost curve. If the minimum average cost is lower for the firms of one country, then they will uniformly outcompete the firms of the other country. I shall consider some changes in the model that will remove this knife-edge property. But it does accord with some observations; for example, in so far as Japanese policies can be credited with their dominance in parts of the semiconductor industry, the amounts of financial support for the entire VLSI and fifth generation computer projects seem very small (Krugman 1984, p. 82). My model suggests that very little assistance may be sufficient for a lot of dominance in high-technology industries. However, the social desirability of doing so remains highly questionable.

2. One firm's R&D strategy

To set the stage for international technological competition and policy, in this section I shall outline the basic model of R&D to be used, and examine the optimal strategy of one firm. The model follows Lee and

Wilde (1980); see also the review and analysis in Kamien and Schwartz (1982, Chapter 5).

The innovation race starts at time 0, and will be seen from the viewpoint of one selected entrant firm. It incurs a one-time entry cost K, and chooses an intensity of R&D effort x. The environment being stationary, this intensity is maintained at a constant level until the race has been decided. Conditional on the innovation not having occured by time t, the probability of our selected firm doing so over the time interval $(t, t+dt)$ is $f(x)\,dt$. The flow conditional probability of success, $f(x)$, is called the 'hazard rate' for the firm. The function f is assumed to have the following properties:

$$f(0) = 0, \quad f'(x) > 0 \quad \text{and} \quad f''(x) < 0 \quad \text{for all } x,$$
$$f'(0) = \infty, \quad f'(\infty) = 0. \tag{1}$$

An initial range of increasing returns in f could be allowed. But the firm's choice of x will not occur there, and the entry cost K already yields initially increasing returns. Therefore I shall omit this complication. The flow cost of the R&D effort is bx. The winner's prize is W, while each loser gets L, both being present values at the date of the innovation, computed using an interest rate r. I shall assume $W > K > L$.

The values of W and L can be made explicit by modelling the continuation game that follows this R&D race. For example, if the innovation is drastic, the winner is a monopolist in the product market, and W is his capitalized monopoly profit. If the innovation is not drastic, the product market can be an oligopoly where the winner has a cost advantage; W and L will be profits in such a game. There may be licensing; this will affect W and L further.[1] There may be future R&D races, and the experience gained in winning or losing this race may affect those future prospects.

Such specific interpretations of W and L are immaterial for my purpose. Therefore I shall save space and algebra by leaving them implicit, that is, by not modelling continuation games explicitly. Likewise, I shall not consider the trivial extension of the model where the race ends with a complete ranking of all participants, and prizes $W_1 > W_2 > \cdots > W_n$.

The parameters W, L, K, b, and r can also be influenced by the policies of various kinds. For example, W and L can be altered by antitrust, trade, and production tax or subsidy policies, K and b

[1] See Katz and Shapiro (1985) for the importance of licensing.

relate to R&D taxes or subsidies, and r is affected by capital taxes or subsidies. The policies may be already committed to, or ones that the firms can rationally anticipate the government will follow in each eventuality. In the next section, all the exogenous variables and policies, and therefore all five parameters, will be allowed to be country-specific.

Let Z denote the sum of the f values for all the *other* firms, and S the corresponding sum for *all* firms including our selected one, that is, $S = Z + f(x)$. In words, Z is the hazard rate for the rest of the industry, and therefore measures the degree of rivalry faced by our firm, while S is the hazard rate for the whole industry. Using this notation, we can compute some important probabilities. That of no innovation by time t is $\exp(-St)$. The unconditional probability that our selected firm wins in the interval $(t, t+dt)$ is $\exp(-St)\, f(x)\, dt$, and that of this firm losing in the same interval is $\exp(-St)\; Z\, dt$. Next, if the race is decided at time t, then our selected firm incurs the flow of expenditures $b\,x$ over the interval $(0, t)$, which has a present value of $b\,x\,[1 - \exp(-rt)]/r$.

With all this information, we can write down π, the expected present value payoff to the selected firm. We have

$$\pi = \int_0^\infty W e^{-rt} e^{-St} f(x)\, dt + \int_0^\infty L e^{-rt} e^{-St} Z\, dt - \int_0^\infty bx\, [(1 - e^{-rt})/r] e^{-St} S\, dt,$$

which simplifies to

$$\pi = \frac{f(x)W + ZL - bx}{f(x) + Z + r} - K. \tag{2}$$

Assuming Nash behaviour, this firm will choose x to maximize π taking Z as fixed. The first-order condition for that is

$$[f(x) + Z + r][f'(x)W - b] - [f(x)W + ZL - bx]f'(x) = 0. \tag{3}$$

The concavity of f is sufficient to ensure that the second-order condition holds at any stationary point defined by (3).

Substituting from (2) in (3), we get

$$f'(x) = b/(W - K - \pi). \tag{4}$$

In the following sections, I shall use this formulation of the firm's optimization as a component of industry equilibrium in one country, and with international trade. To set the stage for that analysis, it helps to know the comparative statics of the firm's problem as the degree of rivalry Z changes.

Write the firm's expected profit as $\pi(x, Z)$, the optimum choice of R&D intensity as $x(Z)$, and the maximized profit as $\pi(x(Z), Z)$. Then we have

$$\begin{aligned} d\pi(x(Z), Z)/dZ &= \pi_2(x(Z), Z) \\ &= (L - K - \pi)/[f(x) + Z + r] \\ &< 0. \end{aligned} \tag{5}$$

The first step follows from the envelope theorem, the second on differentiating (2) and simplifying the resulting expression, and the last step from $L < K$ and $\pi \geq 0$.

Likewise we have

$$\pi_{12}(x(Z), Z) = \frac{f'(x(Z))(\pi + K - L)}{[f(x(Z)) + Z + r]^2} > 0. \tag{6}$$

Then, using the second-order condition $\pi_{11} < 0$, we find

$$x'(Z) = -\pi_{12}/\pi_{11} > 0. \tag{7}$$

Finally,

$$dS/dZ = 1 + f'(x(Z))x'(Z) > 0. \tag{8}$$

In concluding this section, I should point out that there is an alternative model of R&D competition, due to Loury (1979) and Dasgupta and Stiglitz (1980). Kamien and Schwartz (1982, Chapter 5) give a parallel exposition. In that model, the expenditure $b\,x$ is incurred as a capital sum at time 0. Then

$$\pi = [f(x)\,W + Z\,L]/[f(x) + Z + r] - b\,x.$$

This formulation yields the same qualitative results on international competition and policy; in particular, the knife-edge property persists. Therefore I shall confine my discussion to the flow expenditure model outlined above.

3. Industry equilibrium in a closed economy

This is a brief recapitulation of the results of Lee and Wilde (1980) in preparation for my treatment of international competition. Suppose that the country in question allows free entry. Suppose all potential firms have identical costs of R&D. Ignore integer problems; I shall consider their effect briefly later. Now each entrant to the race has zero expected profit. Therefore each firm's first-order condition (4) becomes

$$f'(x) = b/(W - K). \tag{9}$$

This has a unique solution for x since f satisfies (1). Then we can solve for S using (2), and recalling $Z = S - f(x)$. This gives

$$S = [\,f(x)(W - L) - b\,x - r\,K\,]/(K - L), \tag{10}$$

where x is defined in terms of w, K and b by (9). Thus the industry hazard rate can be expressed in terms of the exogenous parameters. Recall that $W > K > L$; I shall also require that and that b and r are sufficiently small (I do not need the exact conditions), to ensure a positive solution for S. The number of entrants to the race is given by $n = S/f(x)$.

It will be useful to define a new function, $G(W, L, K, b, r)$, as the right-hand side of (10) when the value of x is defined by (9). Thus G yields the equilibrium hazard rate for the industry as a function of the parameters. It is easy to verify that G is increasing in W and L (the reward parameters), and decreasing in K, b and r (the cost parameters).

An alternative interpretation of $G(W, L, K, b, r)$ is that it is the highest industry hazard rate compatible with non-negative profit for each firm. To see this, note that by (9) the industry hazard rate S and the degree of rivalry Z faced by any one firm move together, and by (5) an increase in the degree of rivalry reduces each firm's profit. Therefore an industry hazard rate higher than that in the zero-profit equilibrium would mean losses for all firms.

This idea proves useful when we consider the socially optimal structure of the industry. First ignore consumer surplus, that is, suppose the winning monopolist can extract it all. Let the parameter values be W_0, L_0, K_0, b_0, and r_0 in the absence of an active policy. Begin by considering a very comprehensive policy. Allow direct control over the number of firms, n, and the R&D intensity of each, x. Let taxes or subsidies change the first four parameters to W, L, K, b. For algebraic simplicity, I shall omit capital taxes or subsidies, thus keeping $r = r_0$, although the analysis can be extended to cover these policies with identical results. Now the industry's expected profit, say Π, is given by

$$\Pi = n\,\pi = \frac{n\,[f(x)W + ZL - bx]}{f(x) + Z + r} - n\,K. \tag{11}$$

To calculate the government's expected net tax revenue, note that, as of the date of the innovation, the winner pays $(W_0 - W)$ of taxes in net present value (subsidy if negative). Each of the $(n-1)$ losers pays $(L_0 - L)$. If the race ends at time t, each of the n entrants makes a net payment of $(b - b_0)[1 - \exp(-rt)]/r$ in taxes on the flow costs of R&D. Finally, each entrant pays net $(K - K_0)$ on the initial costs. Multiplying by probabilities, and discounting back to 0, as was done when calculating each firm's expected profit, we find the expected net tax revenue R to be

$$R = \frac{(W_0 - W)S + (n-1)(L_0 - L)S + nx(b - b_0)}{S + r_0} + n\,(K - K_0). \tag{12}$$

Using $n\,f(x) = S$, the expected social welfare Ω is given by

$$\Omega = \Pi + R = \frac{W_0\,S + (n-1)\,L_0\,S - n\,b_0\,x}{S + r_0} - n\,K_0. \tag{13}$$

This is just the expected profit of an industry when the parameters are $(W_0, L_0, K_0, b_0, r_0)$ and the industry hazard rate is S. Define $S_0 = G(W_0, L_0, K_0, b_0, r_0)$; as we saw earlier, this is the highest hazard rate consistent with non-negative profit. Therefore

$$\Omega < 0 \quad \text{if and only if} \quad S > S_0. \tag{14}$$

It is always possible to attain $\Omega = 0$ by refraining from any policy measures and letting the industry settle into its free entry equilibrium. The socially optimal industry hazard rate must therefore be *less* than that under *laissez-faire*. The reason is that each firm's marginal R&D effort increases the degree of rivalry faced by all the others, and lowers their expected profits. In acting non-cooperatively, firms ignore these effects and thereby reduce the profit for the industry as a whole, and for society.

We can calculate the socially optimal values S, n and x by maximizing (13). Call the results S^*, n^* and x^*. Of course $S^* < S_0$. The precise formula is not needed here; see Lee and Wilde (1980) for details. The first-order condition defining x^* can be written

$$b_0\,[f(x) - x\,f'(x)]/f'(x) = K_0\,(S^* + r_0) - L_0\,S^*. \tag{15}$$

The right-hand side is positive since $K_0 > L_0$ and $r_0 > 0$; the left-hand side is increasing in x. Therefore we have a unique solution.

Such an optimum can be achieved by any of three methods. First, under public ownership or control, n^* and x^* could be chosen directly.

Second, entry restrictions could fix n^*, and a Nash game among the selected firms would achieve x^*. The third method uses anonymous tax and subsidy policies. The choice of W, K and b is made to ensure

$$f'(x^*) = b/(W - K). \tag{16}$$

The parameters are further restricted by

$$G(W, L, K, b, r) = S^*. \tag{17}$$

This still leaves three degrees of freedom. The tax or subsidy rates are implicitly defined by $(W_0 - W)$, etc. The ensuing free-entry equilibrium is socially optimal.

The only difference among these methods is one of distribution. Under public ownership or tax-subsidy policies, the social profit accrues to the government; with entry restrictions it goes to the selected firms. In this model the difference is of no concern, but in reality one would suspect different rent-seeking responses leading to substantive differences.

If there is unappropriated consumer surplus, these conclusions change somewhat. Let C denote the present value of the future increase in such surplus as of the date of the innovation. Then the contribution to welfare coming from expected consumer surplus is easily seen to be $CS/(S+r)$. This makes a larger industry hazard rate, leading to faster innovation, socially desirable. The over-all choice is then governed by the balance between this effect and the negative interaction in the profits of the firms. The relation between S^* and S_0 becomes ambiguous.

4. International R&D competition

Consider two countries whose firms can engage in the innovation race. The winner's monopoly rents may come from markets in either of these two countries, or some others not engaged in R&D. The parameters W, L, K, b, and r can differ for the two countries' firms; use subscripts $i = 1$ and 2 to identify them. This can capture a wide range of natural advantages and policy differences: (1) the winner's and the loser's prizes W_i and L_i can differ because of production cost difference, the two governments' policies with regard to market access for own and rival country firms, patents, licensing, regulation, taxation, etc., and perhaps differences in access to third markets, (2) the K_i and b_i can differ because of cost differences in conductiong R&D, and the two countries' tax or subsidy policies, (3) the r_i can differ because of natural or policy-induced differences in the cost of capital, unless there is perfect international mobility of capital.

I shall assume for a while that all the firms within one country are identical in their costs, tax treatment etc., and there are no barriers to entry in the race. Accordingly, I shall look for an equilibrium where all the active firms in one country choose the same level of R&D effort. Let us first look for an equilibrium with active firms in both countries. Let there be n_i firms, each with the effort level x_i, in country i. Then

$$S = n_1\, f(x_1) + n_2\, f(x_2). \tag{18}$$

Further, each firm will choose x_i optimally as discussed in the previous section, and each will have zero expected profit. Then (9) and (10) become, for $i = 1$ and 2,

$$f'(x_i) = b_i/(W_i - K_i), \tag{19}$$

and

$$\begin{aligned} S &= [f(x_i)(W_i - L_i) - b_i\, x_i - r_i\, K_i]/(K_i - L_i) \\ &= G(W_i, L_i, K_i, b_i, r_i). \end{aligned} \tag{20}$$

Combining (20) for the two countries, we have

$$G(W_1, L_1, K_1, b_1, r_1) = G(W_2, L_2, K_2, b_2, r_2). \tag{21}$$

Each side is determined by an independent set of exogenous parameters. Therefore the equality can be true only in an exceptional set of circumstances. Unless it holds, we cannot have an equilibrium in which both countries' firms are active in R&D. This is the 'cutting edge' result mentioned in the introduction.

Let us examine which country will capture the entire R&D activity when (21) is not satisfied. Consider an equilibrium where country 1 has active firms, but a country 2 firm would make a negative expected profit if it were to choose its best positive x_2. Then (19) and (20) hold for $i = 1$, while for $i = 2$, the first order condition (4) and the definition of expected profit (2) can be written

$$f'(x_2) = b_2/(W_2 - K_2 - \pi_2), \tag{22}$$

and

$$\frac{f(x_2)\, W_2 + Z_2\, L_2 - b_2 x_2}{f(x_2) + Z_2 + r_2} - K_2 = \pi_2 < 0, \tag{23}$$

where $Z_2 = S - f(x_2)$. Solving (23) for S and using (22), we have

$$S = G(W_2, L_2, K_2 + \pi_2, b_2, r_2). \tag{24}$$

Since the function G is decreasing in the K argument, and $\pi_2 < 0$, we can combine (24) with (20) for country 1 to write

$$G(W_1, L_1, K_1, b_1, r_1) > G(W_2, L_2, K_2, b_2, r_2). \tag{25}$$

In other words, the country with the larger value of G has the edge in R&D. If the two countries start equal, the slightest favourable policy in country 1 will give it dominance. This allows the possibility that some policies in country 1 favour its innovating firms while other policies work against them; it is the net advantage embodied in the value of G that determines the outcome.

To understand this result, recall that the function G gives the maximum industry hazard rate compatible with the survival of a firm. Now, if the world industry hazard rate equals the right-hand side of (25), country 1 firms can profitably enter, while the least such entry implies expected losses for country 2 firms and therefore their withdrawal from the race. Then competition among country 1 firms continues, and drives the industry hazard rate up to the left-hand side of (25).

An alternative intuition is to consider one firm's average cost of producing a dollar of expected revenue. Using (2), and omitting country subscripts, this can be written in terms of the effort level as

$$\begin{aligned} c(x) &= \frac{bx + K\,[f(x) + Z + r]}{f(x)\,W + ZL} \\ &= \frac{K}{W} + \frac{bx + K\,[Z(W - L) + rW]}{W\,[f(x)\,W + ZL]}. \end{aligned} \tag{26}$$

It is easy to see that this is U-shaped. Its minimum occurs when x satisfies

$$[f(x)\,W + ZL]\,b - \{\,bx + K\,[Z(W - L) + rW]\,\}\,f'(x) = 0. \tag{27}$$

Let c^* be the minimum average cost. Using this in (26), substituting in (27), and simplifying, we find

$$f'(x) = b/(c^* W - K).$$

Then (26) can be written as

$$S = G(c^* W, L, K, b, r). \tag{28}$$

Now bring in the two countries. Since they must share the same S, we have

$$G(c_1^* W_1, L_1, K_1, b_1, r_1) = G(c_2^* W_2, L_2, K_2, b_2, r_2). \tag{29}$$

If country 1 has active firms, the zero profit condition becomes $c_1^* = 1$, while if country 2 does not have active firms, this must be because $c_2^* > 1$. When these values are used in (29), we see that it corresponds exactly to our earlier condition (25), since G is increasing in the W argument.

This confirms the intuition that the country whose firms can attain the lower minimum average cost will sweep the other out of the industry. What the formal analysis has done is to establish that the model of the R&D race does have U-shaped average costs, and to give us an exact criterion in terms of the parameters, whereby we can test which country has the edge.

I argued above that there is some empirical evidence for such a knife-edge property, for instance in the semiconductor industry. However, it is the result from a special model. We should see what changes in the model will yield a more continuous response to policy, and assess their significance. There are at least four such modifications.

The first is to allow the costs of R&D to be endogenous. As the advantaged country's firms enter the race, the demand for scientists and other inputs to R&D will increase, which can raise its values of b and K and thus reduce its advantage. This mechanism can balance the two countries' G values at the margin. However, the empirical importance of this is doubtful. The focus of analysis is an innovation in one industry. Entry into this arena will change factor costs appreciably only if the relevant factors are very highly specific to this activity. This seems unlikely in all but the short run. Even with this modification, each country's expected industry profit will be zero, so the profit-capture motive for policy will be absent.

The second possibility is to make the prizes endogenous. For example, this can happen because greater entry in this race implies better prepared entrants in future races, and therefore a quicker erosion of monopoly rents. However, if this is to reduce one country's edge, it is important that each country's W_i is eroded faster by the entry of its own firms. The mechanism for such selectivity is hard to see.

The same comment applies to the third possibility, namely an integer problem. If there are few firms in the race, it is possible that each of n entrants has positive expected profit, while each of $(n+1)$ would have negative expected profit. We expect this to be important in some industries like commercial jet aircraft. But the international knife-edge persists; all n firms must come from the country that has the edge.

The fourth modification is potentially the most important, namely the heterogeneity among firms. For example, suppose there are firms with different b_i in country i. Then (21) holds only for the marginal b_1 and b_2. Policies that favour one country's firms can shift this margin toward it, but the inframarginal firms in the other country will survive and have positive expected profits. Such a model is analysed in Dixit (1988). An empirically plausible case is easy to discuss here. One would expect the inframarginal firms to be the winners of earlier rounds of similar races, who have acquired non-marketable specific assets like information and expertise in the process. But all the marginal entrants to the current round would be on fairly similar footing, with the same possibilities of acquiring the inputs available in open markets. For example, in country 2, there would be a few firms with low b_2, and a large bunch of others with a common higher b_2. If country 1 gives its firms the edge, the inframarginal firms from country 2 will remain in the race, but the knife-edge will cut off all the marginal ones in that country. Such a replacement of one country's marginal firms by another country's marginal firms, of course, achieves no profit-shifting for the aggressor.

To sum up, my judgement is that the pure knife-edge case is an extreme one, but quite substantial shifts in the international location of R&D can be expected from small changes in the policies of countries when entry is open. However, we should not expect any accompanying large changes in expected profits.

5. Normative implications

We saw that, under the circumstances posited in the model, a country can give its firms a decisive edge in an international R&D race. The next question is whether it is socially desirable to do so.

As in §3, I begin by ignoring consumer surplus. This amounts to assuming that the winner can capture it by means of suitable discriminatory pricing, or, as is often done in the profit-capture literature, that all sales are exports to third countries.

Suppose the 'natural' values of the relevant parameters in the absence of any active policy are $W_{0i}, L_{0i}, K_{0i}, b_{0i}$, and r_{0i} in country i

($i = 1{,}2$). Define

$$S_{0i} = G(W_{0i}, L_{0i}, K_{0i}, b_{0i}, r_{0i}), \tag{30}$$

and label the countries so that

$$S_{01} > S_{02}. \tag{31}$$

In other words, country 1 has the decisive edge in R&D when neither country pursues any active R&D policies.

First, consider the optimal policy of the country with the natural advantage, 1. As in §3, it would like to reduce the negative profit interaction among its firms by reducing its hazard rate S_1 below S_{01}. If the optimum, say S_1^*, exceeds S_2, then the country can proceed to implement the optimum policy as in §3 with no fear of entry by country 2's firms. This is analogous to the case of 'blockaded entry' in oligopoly. Otherwise, it will practice an analogue of the case of 'limit pricing', and set S_1 just above S_2 to prevent entry. The appropriate x_1 in either case can be found by the same method as was used when deriving (15).

Next, consider the naturally disadvantaged country's policy. Promotion of its own firms' R&D to make S_2 exceed S_1 is economically costly for country 2 since that makes the negative profit interaction among its firms even worse. If the attainment of dominance in R&D is imposed as a constraint on grounds of national security or prestige, we can calculate the second-best policy. Keeping S_2 at its target value, we will choose n_2 and x_2 to maximize welfare, which will be given by a formula like (13) with the appropriate subscripts. The resultant x_2 will be defined by a condition like (15).

An alternative approach for country 2 may be to lower the hazard rate attainable by country 1. Country 2 can lower the payoffs W_1 and L_1 for firms of country 1 below their natural values W_{01} and L_{01} by imposing trade restrictions. It can raise the costs K_1 and b_1 above K_{01} and b_{01} by denying country 1 firms access to specific inputs, or refusing to admit country 1 workers for some special training.[2] If such measures of sufficient severity are available, then S_1 can be lowered below S_2. There may even be room to lower S_2 below S_{02} while keeping it above S_1, thereby achieving dominance and economic profit. Of course, such policies risk retaliation and a mutually harmful trade war.

Finally, introduce consumer surplus. The purest setting in which to consider its effects is one where neither country has a natural edge

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[2] Barry Nalebuff suggested this policy.

in R&D, that is, $S_{01} = S_{02}$, but either can acquire dominance at an infinitesimal revenue cost. Such action would be socially desirable from one country's standpoint if consumer surplus is higher with one's own winner than with a foreign one. This may be so because a government can more easily place a price ceiling on its country's firms, and offset this reduction in W by a sufficiently large reduction in K and b to achieve dominance.

More generally, we saw in §3 that the inclusion of consumer surplus raises the optimal value of S above that indicated by profit and revenue considerations alone. In the international setting, since each country ignores the effect of S on the timing of the other's gain of consumer surplus, their non-cooperative choices of S are too low for world efficiency. Increasing the worldwide industry hazard rate is now an international public good, and each country wants to become a free rider. Thus the incentive for a country to promote its R&D, which we saw in a closed economy when we introduced consumer surplus considerations, is weakened in the international context.

6. Concluding comments

I have argued that the social desirability of promoting high-technology industries should be calculated taking into account the whole equilibrium of the R&D process, and not merely the profits of the eventual winners of the technology race. The model designed to do so showed that small favourable policy shifts at the margin could produce large shifts in the sizes of the R&D industries in the two countries. However, the economic desirability of achieving such dominance in high technology was a much more questionable issue. This was because the netting out of the losers' costs from the winner's profit largely removed the profit-capture motive for policy activism.

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