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DYNAMIC R&D COMPETITION

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ABSTRACT

We study a simple, two-stage, stochastic patent race involving two firms. We examine the behavior of the participants as they gain the lead or fall behind in the race. We find that the leader engages in R&D more intensively than does the follower, and that both firms intensify their efforts if the follower does catch up with the leader. We also analyze (1) the attractiveness of licensing, whereby the leader shares his results with the follower, (2) a policy of issuing patents for intermediate research results, and (3) the effects of research joint ventures, whereby the firms coordinate their initial research efforts and share their results.

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I. Introduction

Technological competition often has several of the characteristics of a race. In a race, the largest (and perhaps only) prize is awarded to the first participant to cross a well-defined finish line. Similarly, the first firm to make an industrial breakthrough often captures the largest share of industry profits. If the discovery is patentable, and "inventing around the patent" is not possible, then second-place finishers may earn nothing at all. In races other than sprints, strategy plays a critical role. The participants adjust their tactics as the race develops, especially in response to changes in their relative positions. Similarly, in technological competition, it is likely that firms will vary their efforts depending upon whether they are ahead or behind in the competition.

The patent-race literature has focused primarily on the first of these analogies behind technological competition and track events. Lee and Wilde (1980) and Reinganum (1981), among others, have investigated thoroughly the determinants of R&D expenditures in situations where the first to succeed captures the largest (or only) prize. Their analyses embody no notion of progress or leadership, however; they study stationary races in which all firms are equally placed until the competition is (suddenly) over.

In this paper we explore the dynamic aspects of R&D rivalry. In particular, we focus our attention on how effort may vary over the course of a competition, as one firm initially gains an advantage over its rival, and then (perhaps) the other draws even again.

Several investigators before us have studied some aspects of non-stationary R&D races. Fudenberg, et. al., (1983) analyze a model of a multi-stage patent race, but they severely restrict the firm's abilities to vary their research intensities. Harris and Vickers (1985) allow for a continuous choice of research effort by firms, but theirs is a deterministic race in which equilibrium is characterized by all firms but one exiting the competition right at the outset. Neither of these specifications is suitable for investigating the dynamics of R&D rivalry. The paper that is closest in spirit to ours is Judd (1985), which allows for progress in the context of a stochastic competition. The applicability of that analysis is limited, however, by the assumption that the winner's prize is of arbitrarily small value.

Our approach is to extend, in a very straightforward way, the familiar patent race formulation of Lee and Wilde (1980). We adopt their stochastic structure, but allow for progress (and the possibility that one firm may be ahead of another) by introducing a single intermediate step in the research program facing each firm. Thus, to win the race, a firm in our model must complete two phases of R&D of equal difficulty. The two stages may be thought of as research and development, respectively. Each firm is fully informed about the state of progress of its rival and thus knows immediately if it has taken a lead or fallen behind. Even with this very simple structure, we find a rich set of possibilities, depending on the various parameters of the model, for the dynamics of the race. The theoretical ambiguities that we uncover and discuss are bound to be present in more complex specifications of multi-stage races.

After describing our model of a two-stage race in the next section, we proceed in Section III to characterize the dynamics of duopolistic R&D competition. Then, in Section IV, we turn to a different set of issues that arise in the context of multi-phase R&D rivalries. These concern the incentives that exist for various forms of cooperation or competition at different stages of a technological race. We explore three alternative institutions that alter the dynamics of R&D rivalry. First, the leader may share its intermediate results with its competitor under a licensing agreement. Second, the government might grant a patent to the first firm to achieve an intermediate result, thereby precluding the continued participation in the race of the loser in the initial phase. Finally, the firms may establish a common facility for early-stage research (i.e., form a research joint venture), and then compete noncooperatively in the development phase to turn basic research results into marketable products. We investigate the effects of each of these alternative institutional arrangements on the joint profits of the firms. Our analysis provides guidence in understanding the circumstances under which these forms of cooperation are most likely to arise.

The paper concludes with a brief summary of the findings.

II. A Model of a Two-Stage Race

Two risk-neutral firms compete for a prize of (current) value W. Each discounts future expenses and earnings at rate r. The prize accrues to the first firm to complete a research program involving two stages. At each point in time a firm can choose to remain active by bearing a fixed cost of $f \geq 0$ per unit time[1] and can achieve a flow probability (hazard rate) of success at its current stage of p per unit time by spending a total amount, including the fixed cost, of c(p) per unit time.[2] We assume that $c(0) = f$, and $c'(p) > 0$ and $c''(p) > 0$ for all $p > 0$. The last of these assumptions reflects diminishing returns to R&D effort, due,

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1. Sunk costs incurred at the start of the race would not alter the analysis so long as both firms chose to incur them. If only one firm sinks these up-front R&D resources, the problem reduces to one of monopoly, which we have analyzed in an earlier paper, Grossman and Shapiro (1985).

2. Note that we are assuming that the two stages of research are equally difficult, i.e., the same c(p) function applies at both stages.

for example, to the existence of some fixed factors in the research process such as a limited supply of promising ideas or talented researchers.

Successful completion of the first stage of the program yields an "intermediate result". This result has no intrinsic value, but its attainment is a prerequisite for beginning work on the ultimate phase of research. We assume that each firm can observe the state of progress of its rival, i.e., whether the rival has successfully completed the first stage of research or not.[3] Clearly, when one firm has completed the first phase and the other has not, we have a situation where the former is ahead of the latter in the technological race.

At every point in time, the game we have described can be fully characterized by the state of progress of each firm. Three types of situations are possible: (i) when neither firm has achieved the intermediate step; (ii) when one firm (the leader) has completed the initial phase of R&D, but the other (the follower) has not; and (iii) when both firms have advanced to the final stage of research. Each firm chooses whether to remain active, and if so, its instantaneous rate of expenditure on R&D, as a function of its own position in the race and that of its rival. We shall refer to p, a firm's flow probability of achieving a breakthrough in its current phase of research at any instant, as its "speed" or "intensity of effort".

We employ for this two-stage race the solution concept of sub-game perfect Nash equilibrium. We must, therefore, determine for each possible configuration the effort devoted to R&D by each of the firms. We denote by p_{ij} the per-unit-

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3. It would be interesting to explore the (realistic) game of imperfect information that arises when there are lags in observing the progress of one's rival. Such an analysis, which is more complex than the one carried out here due to the continual updating of beliefs and thus behavior by each firm, is beyond the scope of the present paper.

time probability of success of a firm that has completed i stages of the research program facing a competitor that has completed j stages, for i and j equal to zero or one. The firms choose their R&D intensities to maximize expected discounted net profits. The pair of speeds determines the expected payoffs to the rivals, given the current state of the game. We write these as V_{ij}, using the same subscripting convention as for the hazard rates.

The analysis begins with the most advanced state and works backward. If each firm already has achieved the intermediate result, the situation is that described by Lee and Wilde (1980), with their arbitrary market structure replaced by that of duopoly. If, in such circumstances, firm A chooses an R&D intensity p^A and its rival, B, chooses p^B, then its expected payoff V^A is given implicitly by

$$rV^A = -c(p^A) + p^A(W - V^A) + p^B(-V^A) \tag{1}$$

This equation states that the rate of return on the asset V^A is equal to the flow of "dividends", $-c(p^A)$, plus any expected capital gains, $p^A(W - V^A)$, and losses, $p^B(0 - V^A)$. Solving for V^A yields

$$V^A = \frac{p^A W - c(p^A)}{r + p^A + p^B} \tag{2}$$

Taking p^B as given, firm A chooses p^A to maximize V^A. Observe that firm A will remain active provided that there exists a value of p^A that makes V^A positive. Such a p^A will exist if and only if $W > c(p^*)/p^* \equiv \alpha$, where p^* is the speed that minimizes the cost per unit probability of success, $c(p)/p$, and α is the minimal average cost. Assuming that this condition is met, differentiation of (2) gives the first-order condition for firm A's speed:

$$c'(p^A) = W - V^A \tag{3}$$

This condition indicates that a firm's effort is directly related to the size of the capital gain it will earn if a breakthrough is achieved.

Equation (3) also tells us that the rivals have upward-sloping reaction curves in (p^A, p^B) space. The greater is firm B's expenditure rate on R&D, the more firm A will find it optimal to spend on its own research program. The reason is that an increase in firm B's expenditure rate reduces V^A and hence increases the capital gain that firm A would enjoy were it to achieve a laboratory success. This property of upward-sloping reaction schedules indeed will apply at all stages of the patent race.[4] It implies that R&D expenditures under competitive conditions exceed the collusive rates that maximizes joint profits.[5]

The symmetric equilibrium to the sub-game that results if both firms have advanced to the final phase is found by substituting p_{11} for p^A and p^B and V_{11} for V^A in equations (2) and (3).[6] This substitution leaves the following pair of simultaneous equations:

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4. Straightforward calculations show that for all states of the game a firm's reaction curve is upward sloping if and only if its expected payoff falls when its rival completes a phase of the research program. This condition always applies in the model.

5. If the private payoff to the winning firm coincides with the social benefit of the discovery, then the fact of upward-sloping reaction curves implies that resources will be spent on R&D at a socially excessive rate. This property of stochastic patent races was noted by several earlier authors.

6. Any equilibrium for the sub-game in this state is symmetric, as can be verified from (3). Firm A selects a higher speed than firm B if any only if and only if firm A has a smaller expected payoff. But the payoff for firm B must be smaller than that for firm A if its research effort is less intense.

$$V_{11} = \frac{p_{11}W - c(p_{11})}{r + 2p_{11}} \tag{4}$$

$$c'(p_{11}) = W - V_{11} \tag{5}$$

Next we calculate the equilibrium speeds and expected payoffs when one firm has completed the initial phase of research but the other has not. Consider the leader first. If this firm chooses a speed p_{10} and the follower selects p_{01}, then the equation analogous to (1) is

$$rV_{10} = -c(p_{10}) + p_{10}(W - V_{10}) + p_{01}(V_{11} - V_{10}).$$

The last term here represents the capital loss $(V_{11} - V_{10})$ that results if the follower attains the intermediate result, thereby "catching up." Solving this equation for V_{10} gives

$$V_{10} = \frac{p_{10}W + p_{01}V_{11} - c(p_{10})}{r + p_{10} + p_{01}} \tag{6a}$$

The leader will find it optimal to choose $p_{10} > 0$ if and only if $W > \alpha$, in which case its optimal intensity obeys

$$c'(p_{10}) = W - V_{10}. \tag{7a}$$

Turning to the follower, it is possible that this firm will find it optimal to drop out of the competition. This is the case if and only if the value V_{11}

found from equations (4) and (5) is less than α.[7] Then $p_{01} = V_{01} = 0$, and p_{10} and V_{10} are found by substitution $p_{01} = 0$ into equations (6a) and (7a). If $V_{11} > \alpha$, then the expected payoff to the follower is

$$V_{01} = \frac{p_{01}V_{11} - c(p_{01})}{r + p_{10} + p_{01}} \tag{6b}$$

where p_{01} satisfies the first-order condition

$$c'(p_{01}) = V_{11} - V_{01}. \tag{7b}$$

If the follower remains in the race, then the simultaneous solution of equations (6a), (6b), (7a) and (7b) determines the speeds and values in the leader-follower state.

Finally, we consider the initial phase of the race, that which occurs before either firm has achieved any progress. Applying reasoning similar to that above, we note that any equilibrium at this stage is symmetric. The two firms will embark on the research program if and only if $V_{10} > \alpha$. In this event, we have

$$V_{00} = \frac{p_{00}V_{10} + p_{00}V_{01} - c(p_{00})}{r + 2p_{00}} \tag{8}$$

and

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7. Since $V_{11} < W/2$ by equation (4), it is entirely possible that $V_{11} < \alpha < W$, in which case a firm will begin the race but drop out if it falls behind.

$$c'(p_{00}) = V_{10} - V_{00} \tag{9}$$

which jointly determine p_{00} and V_{00}.

Solving the entire two-stage race now is merely a matter of recursive solution of the various sets of equations for each possible state of the game. In general, it is not possible to obtain explicit formulas for the optimal speeds. Nonetheless, we are able to characterize the strategies that are chosen by firms involved in a two-stage duopolistic patent race. This we do in the next section.

III. The Pattern of R&D Expenditures

In this section we examine how a firm engaged in a race alters its behavior over time, when it pulls ahead of or falls behind its rival, and when it or the rival draws even again. Our main conclusions are that the leader always devotes more resources to R&D than does the follower, but if the latter happens to catch up, both firms intensify their efforts. Regarding the transition of the race from its initial state to one where one of the firms pulls ahead, we find that it is theoretically possible for either or both firms to speed up or slow down in the event of an intermediate breakthrough by one of them. Numerical simulations conducted over a wide range of parameter values for our model (with a particular functional form for the cost function) suggest that perhaps the most typical outcome is one where the firm that takes the lead intensifies its effort as a consequence, while its rival reduces its rate of spending.

We establish first that the (former) leader augments its R&D efforts when its rival succeeds in attaining the intermediate result, i.e., $p_{11} > p_{10}$. From equations (5) and (7a) and the fact that $c'' > 0$ it is immediate that $p_{11} > p_{10}$ if and only if $V_{11} < V_{10}$. Arguing by contradiction, suppose that $V_{11} > V_{10}$ and hence

$p_{10} > p_{11}$. In this event, it is easy to show (by differentiating V_{10} in (6a) with respect to p_{01}) that the leader's reaction curve must be downward sloping. But then p_{10} must be smaller than the leader's optimal response to $p_{01} = 0$, say $\hat{p}$. But $\hat{p}$, which maximizes $[pW - c(p)]/(r + p)$, also is the optimal speed for a firm facing a rival who has also completed the initial stage, if the latter happens to choose to devote no resources to R&D. Since the reaction curves in the state when both firms are working on the second stage of research must be upward sloping, we have $p_{11} > \hat{p}$. It follows, therefore, that $p_{11} > p_{10}$, a contradiction that establishes our claim.

Next we show that when one firm is ahead and the other behind, the leader's speed exceeds that of the follower, i.e., $p_{10} > p_{01}$. In combination with the previous results, this also will serve as proof of our claim that the (former) follower increases its effort if it manages to draw even, i.e., $p_{11} > p_{01}$.

From equations (7a) and (7b) and the fact that $c'' > 0$, $p_{10} > p_{01}$ if and only if $W - V_{10} > V_{11} - V_{01}$. Substituting for V_{10} from (6a) and for V_{01} from (6b) and rearranging terms, this inequality can be written as

$$p_{01}(W - 2V_{11}) + r(W - V_{11}) + (p_{01} - p_{10})V_{11} + [c(p_{10}) - c(p_{01})] > 0 \qquad (10)$$

Again arguing by contradiction, suppose that $p_{01} > p_{10}$. Using the convexity of the $c(p)$ function, this would imply that $c(p_{01}) - c(p_{10}) < (p_{01} - p_{10})c'(p_{01})$. This in turn would imply that

$$\begin{aligned}(p_{01} - p_{10})V_{11} + c(p_{10}) - c(p_{01}) &> (p_{01} - p_{10})[V_{11} - c'(p_{01})] \\ &= (p_{01} - p_{10})V_{01} \qquad (11)\end{aligned}$$

where the equality follows from equation (7b).

We now can show that if the inequality in (11) is satisfied, that in (10) must be so as well. Inequality (11) implies that the sum of the last two terms in (10) is positive. But $W > 2V_{11}$ (see equation (4)), so the first two terms of (10) are also positive. Thus, under the working hypothesis that $p_{01} > p_{10}$, which gave us inequality (11), inequality (10) is satisfied, implying $p_{10} > p_{01}$. This contradiction establishes that in fact $p_{10} > p_{01}$, i.e., the leader's speed exceeds that of the follower.

Our result that both the leader and the follower redouble their efforts if the race becomes tied reflects the fact that the former has more to lose and the latter more to win when the competition is even than when one firm is ahead. The tendency to speed up is exacerbated by the positive competitive response of each to the change in behavior of the other.

Comparing the two states of the game that have the two firms on equal footing, we find that the intensity of competition is greater after the intermediate result has been attained by each. To see this, note from equations (5) and (9) that $p_{11} > p_{00}$ if and only if $W - V_{11} > V_{10} - V_{00}$. But the fact that $p_{10} > p_{01}$ implies that $W - V_{10} > V_{11} - V_{01}$, or $W - V_{11} > V_{10} - V_{01}$. It is straightforward (and intuitive) but tedious to show that $V_{00} > V_{01}$, i.e., that falling behind at the initial stage of the race entails a capital loss. It follows therefrom that $W - V_{11} > V_{10} - V_{00}$ and that $p_{11} > p_{00}$.

Finally, we compare the starting speeds with those that are chosen after one firm has captured a lead in the patent race. We have established by means of constructed examples that any relationship between p_{10}, p_{01} and p_{00} with $p_{10} > p_{01}$ is a possible outcome. After explaining why this is the case, we report numerical simulation results which explore the comparative statics of our model in order to gain an understanding of when the various possible dynamic paths are most likely to occur.

First consider the behavior of a firm that pulls ahead in the race. On the one hand, its rival may react to having fallen behind by reducing its speed or even by dropping out of the race entirely. Given the fact of upward-sloping reaction curves, this diminished rivalry effect tends to cause the leader to moderate its efforts. On the other hand, the leader has advanced towards the finish line by making the intermediate discovery. This pure progress effect tends to cause the leader to increase its expenditures on R&D, so long as the discount rate is positive. In fact, we have shown in Grossman and Shapiro (1985) that a single firm pursuing a multi-stage research program of the form analyzed here will, absent rivalry, always increase effort with each increment of progress, provided that $r > 0$.

The follower also is subject to conflicting forces. The fact that its rival already has achieved the intermediate result means that its reward from completing the initial task is smaller, i.e., $V_{11} < V_{10}$. This diminution of the potential reward to a breakthrough might cause it to reduce the intensity of research or to abort the program altogether, independent of the leader's pace. If, however, the follower chooses to continue racing, and if the leader speeds up upon making the intermediate discovery, then the follower actually may increase its efforts in a positive (upward-sloping reaction) to the leader's increased outlays.

We simulated the model under the assumption of a constant elasticity of variable costs, $c(p) = f + p^e$, for a range of elasticities, e, greater than one.

We also varied extensively the other parameters of the model, W, r and f.[8] We found that, if the follower drops out of the contest ($p_{01} = 0$), then the leader increases its speed ($p_{10} > p_{00}$) if the interest rate is large. A high interest rate implies a dominant pure progress effect. The leader also is more likely to speed up when the rival exits the race if the elasticity of the cost-of-progress function is large. In such circumstances, because it is costly to increase the probability of discovery, competition at the start of the race does not push the speeds to very high levels. Then, when one firm drops out upon falling behind, the removal of the competitive interaction does not have a quantitatively large impact on the behavior of the remaining firm.

For most of the combinations of parameter values that we investigated, if the follower remains active, then the leader works more intensively after the completion of the initial phase of research than before. We did find examples with $p_{00} > p_{10} > p_{01} > 0$, however; these occurred for small values of e.

Turning to the behavior of the follower, this firm is most likely to cease its research operations upon falling behind if fixed costs are large, the prize is small, the elasticity of the cost function is large or the discount factor is large.[9] If this firm does remain active, it is likely to reduce the size of its R&D expenditures. Indeed, in all of our simulations we did not find a single instance where the competitive response to the actions of the leader was sufficiently large for the firm that fell behind to intensify its efforts.

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8. The ranges over which parameters were varied are as follows: W from 20 through 500, f from 10 through 200, r from 0 through 100, and e from 1.5 to 8.0. For the most part, these ranges were determined by the computer's numerical limitations.

9. For the constant elasticity cost function the stopping rule for the follower is $V_{11} < \alpha = e[f/(e-1)]^{(e-1)/e}$. Large values of r and small values of W yield small values for V_{11}.

However, a simple analytical example suffices to demonstrate that such an outcome cannot be ruled out on theoretical grounds. Suppose that the discount rate is zero and only two levels of effort are possible, these yielding flow probabilities of discovery per unit time of q_1 and q_2 with $q_1 < q_2$. The cost of research is nil if q_1 is chosen, while $c(q_2) = \bar{c}$. Then, if

$$\frac{q_1 + 3q_2}{q_2} < \frac{W(q_2 - q_1)}{\bar{c}} < 4$$

a unique equilibrium exists in the race and has $p_{00} = q_1$ and $p_{01} = p_{10} = p_{11} = q_2$. In this example, each firm would prefer to proceed at the slower pace throughout the race provided that its rival did so as well, but each speeds up after the initial phase in response to the other's having done so.

Pulling our findings together, we depict in Figure 1 a typical pattern for a two-stage R&D race. At time t_1, firm A attains the intermediate result and begins work on the final stage of the research project. Sensing victory, this firm intensifies its efforts, while a discouraged firm B reduces the scope of its operations. At time t_2, firm B achieves a breakthrough in its phase-one research, and draws even in the race. Thereafter the firms compete intensively, until the final stage is completed by one of them at t_3, and the patent is awarded.

IV. Licensing Arrangements, Intermediate Patents and Research Joint Ventures

We turn now to a variety of questions regarding the incentives that firms have to cooperate (partially) during the course of a multi-stage patent race. Our analysis focuses on three institutional arrangements that are observed in some, but not all, instances of technological competition. These are: (i) licensing contracts, whereby the leading firm in an industry shares its superior knowledge with one or more of its rivals in exchange for the payment of a royalty fee; (ii) the granting of "intermediate patents", whereby the leading firm in a technological race is declared by the policy authority to be the winner before it has completed all the stages of development of an innovation that are necessary to yield a marketable product; and (iii) research joint ventures, whereby the firms agree to join forces in conducting certain phases of a larger research agenda. Our analysis sheds light on what factors influence the attractiveness to the firms of these various arrangements.

A. Licensing

Once one firm in a multi-stage patent race has concluded an initial phase of research that its rivals have not, the leader may have an incentive to make its findings available to some of the other firms for a fee. Of course, certain informational and bargaining obstacles will need to be overcome before an agreement can be reached. These are beyond the scope of the present paper, as we address only the issue of whether or not there are potential gains from trade in information (i.e., the intermediate result) in our model.

The question of the existence of potential gains from trade involves a comparison of total industry "profits" with and without a licensing arrangement. If licensing occurs, both firms will be engaged in the final stage of research with a joint value of $2V_{11}$. In the absence of licensing, the firms together enjoy expected profits of $V_{10} + V_{01}$. So, in our model, licensing can increase joint profits if $2V_{11} > V_{10} + V_{01}$.[10]

Licensing is jointly attractive to the firms because it allows the follower to advance towards the finish line without expending further resources on the intermediate result.[11] Clearly, in any realization of the race in which the follower eventually draws even, the firms ex post would wish they had concluded a licensing agreement. In addition, a licensing arrangement causes the follower to remain in the competition in situations where dropping out is otherwise optimal for this firm. While this may involve a waste of resources (if the leader is the first to make the final discovery in any event), it can enhance industry R&D efficiency. So long as the fixed costs, f, are not too large, the increasing marginal costs in any particular laboratory imply that a given probability of success can be achieved more efficiently by operating two labs rather than one. This increased efficiency effect is most pronounced when the firms are in a rush to reach the finish line, i.e., when the future is heavily discounted.

Licensing also has a drawback from the perspective of the two firms in a dupolistic patent race. A licensing agreement is bound to intensify competition between the firms, since p_{11} exceeds both p_{10} and p_{01}. Absent licensing, the

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10. Of course, the feasibility of licensing will alter firms' incentives at the start of the race. This ex ante effect may stimulate or retard the discovery of the intermediate result by one of them, depending upon how the gains from trade will be split between the licensee and the licensor. See Katz and Shapiro (1984a and 1984b) and Shapiro (1985). Due to the existence of this ex ante effect, the firms may seek ways of pre-committing not to license to their rivals even in instances where ex post gains from trade will be available. Such means of pre-commitment may be difficult to find.

11. A second lab could also be put to work on the final research stage if the leader could acquire the follower's laboratory. If feasible, this would clearly dominate licensing, as the two labs' research intensities could be set cooperatively. We assume that it is not possible to trade the specific assets that constitute a lab.

period of intense competition might be avoided altogether, if the leader completes the research program before the follower makes any progress. Indeed, this outcome will surely arise in situations where the follower drops out of the race. The increased rivalry that licensing engenders may or may not dominate the "resource-free progress" that the follower can achieve by means of this arrangement.

In our simulation exercise we found potential gains to licensing in a variety of circumstances. In situations where the follower would drop out absent a licensing agreement, licensing raises industry expected profits when the discount rate is high or, for a given positive discount rate, when the elasticity of the R&D cost function is sufficiently large. A high discount rate makes it optimal for the firms to proceed quickly, and in such cases a second lab with its own supply of ideas and skilled personnel can be especially valuable. Similarly, for a given value of $r > 0$, the larger is the value of e the greater is the efficiency gain from running two labs rather than one. When $r = 0$, however, it is efficient from the industry point of view to operate a single lab at the scale that achieves the minimum average cost of progress, α.

In cases where the follower remains active, licensing is most likely to be jointly profitable when the rivalry to which it gives rise in the final phase of the race is not so intense. Thus, a high value of e is conducive to licensing; when the marginal cost of increasing the probability of success is high, the firms will not be tempted to do so to as great an extent. The same reasoning suggests that licensing will be viewed more favorably when the prize is small. Finally, a high discount rate is conducive to licensing, even if the follower stays in the race, because it reduces the expected time to discovery. These intuitive propositions were borne out consistently in our simulations, although we were unable to prove general results using analytical methods.

B. Intermediate Patents

We now inquire as to whether the firms would support ex ante a policy that awarded a patent at the intermediate stage of the innovation process.[12] While current U.S. policy stipulates that patents are to be granted only for "useful" innovations, there may be considerable scope for discretion on the part of the patent-granting authority concerning what satisfies this criterion. A patent may well be awarded at a stage where substantial additional development expenses will be necessary before the product can be made available to consumers.

If an intermediate patent is issued, the firm that fails to make the initial discovery first would be legally required to drop out of the race. From an ex post point of view (i.e., once the intermediate result has been attained by one of the firms), this would raise industry expected profits if the expected payoff to a firm proceeding to the second stage of research without competition, say V_m, exceeds the sum of the two firms' payoffs, $V_{10} + V_{01}$, in the event of continued rivalry. The ex post benefit of an intermediate patent to the firms (which, of course, accrues more than fully to the leader at that stage) is that it removes the extra cost of competition in the later stages of development. The cost of such a patent is that it reduces by one the number of active laboratories, thereby

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12. If the private prize W happens to coincide with the social benefit, as, for example, when the winning firm can practice perfect price discrimination or when all of the resulting product is to be sold in export markets, then the question of whether the two firms would prefer the granting of intermediate patents coincides with the normative question of what should be appropriate patent policy from a social welfare perspective. Of course, in general the private prize and the social benefits will differ. Surplus that accrues to domestic consumers as a result of the discovery causes the social benefit to exceed the private prize, while reductions in profits of firms not active in the race under consideration work in the opposite direction. We do not pursue the social welfare analysis more fully, as the line of reasoning is rather clear. For example, if the consumer benefits are significant, then any policies or institutional arrangements that cause the firms to conduct research more intensively will be relatively more attractive than otherwise.

decreasing the efficiency of research for a given industry-wide probability of success.

In simulations using the constant elasticity of variable costs function, we found $V_m > V_{10} + V_{01}$ except when r is large or e is large. A high discount rate make it desirable to complete the research project quickly. Then it is most inefficient to have one of the labs inoperative, especially if diseconomies of scale are substantial.

The fact that $V_m > V_{10} + V_{01}$ is neither necessary nor sufficient for the firms to favor the granting of intermediate patents, however. The patent regime also effects the intensity of competition, and thus the expected resource expenditure in the initial phase of research prior to the intermediate discovery. If an intermediate patent increases expected industry profits measured from the time that the initial stage has been completed, but it causes competition to be more intense at the outset, then it may lower <u>ex ante</u> industry profits. Similarly, an alleviation of competition at the start of the race can compensate for a shortfall of V_m in comparison to $V_{10} + V_{01}$ and cause the firms to support a policy of intermediate patent awards.

In our simulations we found that for parameters values consistent with $V_m = V_{10} + V_{01}$, competition at the start of the race is more intense under a regime with intermediate patents than under one without. Thus, for a range of parameter values, intermediate patents appear beneficial to the firms (taken together) <u>ex post</u>, but not <u>ex ante</u>. Nonetheless, for combinations of values of r and e somewhat smaller than the ones that yield higher <u>ex post</u> expected industry profits under an intermediate patent regime, the granting of such patents also yields expected benefits to the firms before the race starts.

C. Research Joint Ventures

The final form of potential cooperation that we consider is a research joint venture (RJV). We assume that such a venture enables the firms to coordinate their research activities during the first stage of the R&D program. When the intermediate result is achieved, both firms then have access to it. We do not, however, allow for synergies in research to be enjoyed on account of a joint venture. In other words, we assume that the research technology is unaffected by the formation of an RJV. We also assume that joint research is not feasible during the second stage of the project.[13] This assumption corresponds to an interpretation of the two-stage innovation process where the first stage is "research," a public good, and the second stage is firm-specific "development".

Under the R&D technology we have specified, the firms engaged in a research joint venture may prefer to operate either one laboratory or two. By running only one lab, the firms can conserve on fixed costs of equipment and administration. However, the coordination of efforts and activities which imparts administrative savings may also entail a reduction in the variety of approaches that can be pursued. Given the assumption of decreasing returns to devoting more resources to a fixed supply of ideas and techniques, it may be more efficient for the firms to forego the (fixed) cost savings associated with a unified operation, and to use

13. If feasible, the firms would always choose to coordinate their research activities in our model once the intermediate result has been attained by both of them. Doing so allows the rivals to avoid excess competition in the last phase of the race. However, in many applications, it would not be reasonable to maintain the assumption that the size of the prize would be unaffected by an RJV that allowed both firms to have access to the ultimate innovation. In such circumstances, competition might arise in the product market thereby eroding the monopoly profits attached to the patent. For an analysis of the desirability of RJV's with a single stage of research and subsequent product market competition, see Katz (1984).

the joint venture only as a means to collusively set the research outlays at each of two separate facilities.[14]

In general, an RJV tends to increase the joint expected profits of the patent-race participants for two reasons. First, it eliminates profit-dissipating rivalry at the initial stage of the research program. Second, by ensuring that both firms have access to the intermediate result as soon as a breakthrough is achieved in any lab, it (like licensing) allows the firms to avoid the wasteful duplication of effort associated with the follower attempting to gain a state of knowledge that has already been achieved by the leader. On the negative side, an RJV guarantees that the firms will need to endure the most intensively competitive of the various states of the patent race, that when both firms simultaneously are seeking the final result.[15] Absent an RJV, this potentially costly state can be avoided if the leader happens to complete both phases of the research program before the follower is able to progress to the intermediate point.

In our simulations, we indeed found constellations of parameters such that expected industry profits are smaller with an RJV than with unmitigated rivalry at the initial stage. These arose for large fixed costs or small prizes, in

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14. It is not clear, however, that a research joint venture involving no common research facility, but only an agreement to coordinate research budgets, would win approval from antitrust authorities.

15. In this regard, the RJV is similar to the licensing arrangement, which, as we noted, also is subject to this potential drawback. In fact, in situations where licensing would take place, an RJV is a strictly superior arrangement from the point of view of the two firms. Both regimes ensure transition to a stage where each firm has access to the intermediate result as soon as one of the labs achieves success, but the RJV involves coordination of expenditures at the initial stage as well.

situations where the follower would choose to drop out of the race entirely, absent an RJV.[16]

We have identified a new reason why research joint ventures may fail to appeal to rival researchers. The traditional reason is that joint ventures generally involve increased coordination and administrative costs. Another problem is that a joint venture might reduce the diversity of research paths that are pursued. Even absent these factors, we have shown that an RJV may reduce members' profits by increasing their direct rivalry after the venture's results are made available to its members.

V. Conclusions

In this paper we explored the dynamics of R&D competition that result when two firms engage in a patent race. We adopted a simple structure in which a research program requires the sequential completion of two phases of equal difficulty. Following the literature on single-stage patent races, we assumed that success at each stage is subject to uncertainty, and that the flow probability per unit time of a breakthrough increases when more resources are devoted to the project. This structure was sufficiently rich to allow us to analyze how a firm will alter its behavior if it captures a lead, falls behind in the race, or if it sees a former lead or deficit eliminated.

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16. Note that it is neither necessary nor sufficient for an RJV to be undesirable that the follower would drop out of the race. It is possible to construct a two-speed, no-discounting example, such as the one described in Section III, in which for certain parameter values the follower remains active (albeit at the slow speed) under competition, and yet this regime is preferable to an RJV. And when the follower does cease operations, an RJV nonetheless might be profit-enhancing due to its moderating effect on expenditures at the start of the race.

We found that competition is most intense when both firms are even and each has completed the initial phase of the research project. When a lagging firm draws even with a rival that was formerly ahead in the race, both competitors respond by increasing their research efforts.

We also found that when the two firms are at different stages in the innovation process, the one that is ahead has a greater incentive to invest in R&D than the one that is behind. This result is reminiscent of another proposition in the R&D literature, namely that the firm with lower initial costs in a Cournot duopoly has a greater incentive than its rival to engage in cost-reducing R&D.

The response of either firm to one of them becoming the first to achieve the intermediate result is theoretically ambiguous. Numerical simulations for a wide range of parameter values suggest that a typical pattern has the leading firm increasing its R&D expenditures when it advances to the final phase, while the follower reduces the extent of its research activity.

Finally, we used the two-stage patent race model to study the incentives that rival firms have to engage in various forms of cooperation during the course of a technological competition. The desirability of licensing agreements after one of the firms has achieved some progress, of a public policy that grants patents at an intermediate stage in the innovation process, and of research joint ventures that allow the firms to coordinate their activities in the early stages of an R&D program all hinge on the various parameters of the model. In general, these alternative forms of cooperation are most likely to increase joint expected profits when the competition that would arise absent any such arrangement would be quite intense. Competitive pressures are most severe when the prize being sought is large, the discount factor is high and the marginal cost of augmenting the flow probability of success at each stage of research rises slowly.

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Figure 1

Typical Pattern for a Two-Stage Patent Race