FIRM LEVEL BEHAVIOR IN REPEATED R&D RACES

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INTRODUCTION

In industries like the microprocessor industry quality is advancing rapidly. These improvements contribute to economic growth directly by increasing the quality of home computers and indirectly by increasing the productivity of the workforce. In the economic growth literature as much as 50 percent of growth has been attributed to these and similar improvements in technology.[1] Despite the importance of technological advancement, firm incentives to create better products are not well understood. Technological advancement has traditionally received residual treatment in the literature on economic growth. This literature credits improvements in technology for whatever economic growth cannot be explained by the accumulation of other inputs. In traditional R&D literature, where incentives to innovate have been examined explicitly, innovative episodes are treated as singular events, a treatment that overlooks important relationships that occur across episodes.

In order to better examine the incentives firms have to improve technology, and the resulting impact on growth, a series of quality ladders models has recently been introduced into the growth literature.[2] In quality ladders models, firms respond to profit incentives by devoting resources to R&D. In contrast to traditional R&D models, firms compete in repeated R&D races, and must consider product obsolescence when making R&D decisions.

Although the dynamic structure of the quality ladders models has contributed to our understanding of the intertemporal incentives faced by R&D firms, the relationship between competition in R&D and individual firm R&D behavior has not been well developed in previous versions of the model. This is a direct result of the common assumption that each firm's R&D technology is characterized by constant returns. With constant returns R&D technology each additional dollar of R&D spending adds the same additional probability of R&D success in the industry, regardless of which firm spends the additional dollar or how much each firm has already spent on R&D.[3] In an R&D market where an additional dollar of R&D spending by any firm has the same effect on the industry probability of success, only aggregate industry R&D efforts are important in explaining growth. Individual firm efforts cannot be explained since each industry's aggregate R&D effort can be divided arbitrarily between any number of competitors. However, if R&D technology is characterized by diminishing returns, the effects of an additional dollar of R&D spending on the industry probability of success will differ depending on which firm is spending the additional dollar and how much each firm has already spent on R&D. Then the number of competitors and the R&D behavior of each of the competitors become critical determinants of industry growth rates. This is precisely what is suggested by both the empirical evidence and theoretical arguments pertaining to firm R&D technology.

As a theoretical argument Thompson and Waldo[1993] state that, "... R&D activity does not satisfy the usual justification for constant returns to scale in manufacturing—namely that plants can be replicated." Replicating R&D efforts is largely redundent and adds little to a firm's probability of success. In order to increase its probability of success a firm must pursue a variety of R&D avenues. Presumably the firm will attempt the projects which are most likely to be successful first and proceed to projects with less likelihood thereafter, suggesting decreasing returns to R&D. Empirical studies examining the nature of firm R&D technology support this theoretical argument. Examining the relationship between patents granted and R&D spending, Kortum[1993] reports point elasticity estimates in the range 0.1 to 0.6, while Hall, Griliches, and Hausman[1986] obtain an average elasticity estimate of 0.3. Using market value data, Thompson[1993] obtains an average R&D output elasticity with respect to R&D expenditure of 0.86. Each study suggests diminishing returns to R&D expenditures at the firm level, although the authors caution that interpretation of their studies may be hampered by data constraints and the difficulty of both measuring R&D output and of matching R&D output with R&D inputs. As suggested by both theory and the empirical evidence, a decreasing returns to scale R&D technology is employed in this article. Examination of the quality ladders model with this feature improves our understanding of R&D incentives and the behavior of individual firms in R&D markets.

Although the relationship between competition and individual firm R&D behavior has not been examined in previous quality ladders models, it has been analyzed in single episode R&D models. In a model developed by Glenn Loury[1979] firms invest in R&D at the beginning of an R&D race and incur no further R&D costs for the duration of the race. The initial sunk investment in R&D gives each firm a fixed probability, in each period the race continues, of successfully inventing a new product. The first successful inventor captures exclusive rights to produce the new product and all benefits associated with these rights. With all investment occurring up front, an increase in R&D competition, through greater firm participation, does not affect the costs a firm expects to incur during the race. Greater participation will, however, reduce the liklihood that any particular firm will be the first to succeed in R&D. Therefore, in the Loury model, profit-maximizing firms have an unambiguous incentive to decrease R&D efforts in the face of increased competition. Reexamining Loury's original model, Lee and Wilde[1980] included the R&D costs that firms pay for continuing research. Firm R&D benefits also decrease as more firms participate in the Lee and Wilde model, but the costs of R&D fall as well because firms expect a shorter race and a shorter period of R&D expenditures. Consequently, competition increases firm-level efforts in the Lee and Wilde model instead of decreasing firm-level R&D efforts as in the Loury model.

The conclusions reached in each of the two single episode studies depend critically on the single R&D race format adopted. Without the possibility of further product upgrading both specifications ignore intertemporal effects between R&D races. By examining a quality ladders model I explicitly account for the absent intertemporal effects. Here, the relationship between participation in R&D races and firm R&D effort proves to be negative. This is despite the fact that I adopt R&D technology similar to that used by Lee and Wilde. This result proves the importance of identifying intertemporal effects in R&D markets.

By drawing on elements of both quality ladders growth models and R&D models, the model analyzed here increases our understanding of R&D incentive effects associated with competition and product obsolescence. These incentives are essential to explaining the behavior of firms in industries like the microprocessor industry, where successive innovations continue to push the technological frontier forward. As our understanding of these industries increases, public policy makers will be better positioned to adopt R&D policies that increase economic efficiency and improve standards of living.

The remainder of the paper is organized as follows. In the next section I introduce the R&D technology within the context of the quality ladders model and then show existence of a firm-level unique steady-state equilibrium, exploring the properties of the equilibrium when access to cutting-edge R&D technology is unrestricted. I then examine the relationships between the model parameters and equilibrium outcomes, with particular emphasis on the relationship between participation in R&D races and firm R&D behavior. Welfare implications of the model are then examined before concluding remarks are offered.

THE MODEL

In the economy modeled here there is a continuum of industries indexed by ω on the unit interval [0,1]. Each of the different industries produces a unique variety of consumption goods that substitute imperfectly for goods from the other industries. Within each industry goods are perfect substitutes, differentiated only by quality, where quality is indexed by the integer j. Goods of a particular quality level can only be produced when the quality level is reached through successful R&D. The state-of-the-art good in each industry begins with a quality of one and an initial quality index of $j = 0$. In each industry firms compete in repeated R&D races to create higher quality state-of-the-art goods. The winner of each R&D race increases the quality of the industry's state-of-the-art good by a factor $\lambda > 1$ and increments the state-of-the-art quality index by one. Therefore, $j(\omega, t)$, the quality index of the state-of-the-art good in industry ω at time t, represents the number of successful innovations in an industry up to time t and $\lambda^{j(\omega,t)}$ measures the quality of the state-of-the-art good in the industry at time t.

The Consumer Sector

Identical consumers discount the future at the rate ρ and have demand for goods with quality index j from industry ω at time t equal to $d(j, \omega, t)$. Lifetime utility for each, which extends indefinetly into the future, takes the form

$$U \equiv \int_0^{\infty} \left(\int_0^1 ln \left[\sum_{j=0}^{j(\omega,t)} \lambda^j d(j,\omega,t) \right] d\omega \right) e^{-\rho t} dt. \tag{1}$$

Constrained by their budgets, consumers choose spending patterns that maximize their expected lifetime utility.

With these preferences consumers consider goods within industries perfect substitutes when adjusted for quality and buy only the goods with the lowest price-to-quality ratios.[4] They do, however, value the variety in the different industry products and allocate expenditures equally across industries. Defining expenditures at time t as $E(t)$ each consumer's budget-constrained intertemporal optimization problem dictates that spending evolves over time according to

$$E'(t)/E(t) = r(t) - \rho, \tag{2}$$

where $r(t)$ is the instantaneous rate of return consumers earn by saving. When the interest rate exceeds the rate at which consumers discount future consumption, saving for future consumption is attractive and consumer expenditures increase over time. When the discount rate exceeds the interest rate expenditures decrease over time. In the balanced positive-growth equilibrium examined here, where consumer spending is constant over time, the interest rate is constant and equal to the discount rate at each moment. With identical consumers, aggregate demand at time t for the good with the industry's lowest quality-adjusted price takes the same form as individual demand, $D(\omega, t) = E/p(\omega, t)$, where $p(\omega, t)$ is the good's unit price, and E is aggregate consumer spending.

The Production Sector

The production technology is characterized by constant returns to scale where one unit of labor produces one unit of any good independent of time, industry, or quality. The wage rate is normalized to one, giving each firm a constant marginal cost of one.

Producers within an industry compete in quality-adjusted prices. At time t each consumer will purchase only the lowest quality-adjusted priced goods from an industry. Without loss of generality I assume that whenever two goods share the same quality-adjusted price, consumers will choose to purchase the good of the highest quality. With unitary elastic demand and constant marginal cost, profits are maximized when the state-of-the-art producer with a one-step quality lead charges a price of λ. This limit price allows the firm to exploit its quality advantage and earn profits equal to

$$\pi = E(\lambda - 1)/\lambda. \tag{3}$$

It is assumed that firms will never attempt to imitate the current state-of-the-art good. Imitation may be prohibited directly by broad patent protection or indirectly by positive imitation costs resulting from the need to circumvent narrow patent protection. In the latter case, price competition between the incumbent and imitator eliminates any market power and the imitator is unable to recoup imitation costs.

The Research Sector

Initially the number of firms participating in R&D races in each industry is fixed at n. Then R&D behavior is analyzed as competition increases, up to a perfectly competitive level. Over time, n firms compete in R&D races in each industry, but for each individual race the quality leader will perform no R&D.[5] Therefore, only $(n - 1)$ of the n firms will be competing in an R&D race at any given time. The participating firms hire labor which is devoted to R&D. A firm which devotes l units of labor to R&D will innovate at $\tau(l)$, prior to time t, according to the probability given by

$$\text{prob}[\tau(l) \leq t] = 1 - e^{-h(l)t}. \tag{4}$$

The parameter $h(l)$ measures the instantaneous probability of a successful innovation when l units of labor are devoted to R&D. The expected duration until success is given by $h(l)^{-1}$. Firms pay wages to R&D workers each period until a firm in the race successfully innovates, signaling the beginning of the next R&D race.

Each of the n firms in an industry, independent of industry or time, has this same R&D technology. The function $h(l)$ (see Figure 1) is assumed to be twice continuously differentiable and strictly increasing in l. Increasing returns prevail up to l' for each firm, then decrease beyond l' where $l' \geq 0$. The function $h(l)$ is also assumed to satisfy $h(0) = 0 = h'(\infty)$. Pictures (a) and (b) in Figure 1 illustrate the cases with and without initial increasing returns, respectively.

The average product of labor is maximized at l' (see Figure 1) which is also the point where $h(l)/l = h'(l)$. The labor choice l' proves to be a critical point for firms in making their R&D decisions. Below I show that in any positive growth equilibrium each participant in a R&D race will hire at least l' units of R&D labor.

The Labor Sector

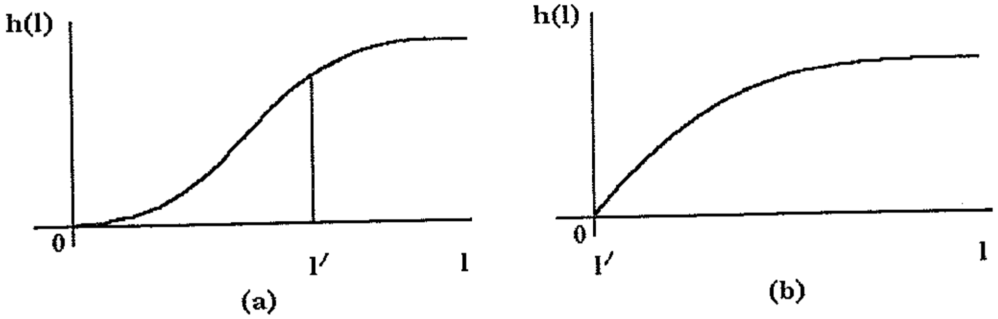
The labor supply is homogeneous, fixed at L, and the labor market is assumed to clear each period. In equilibrium the share of labor devoted to production is given by E/λ. The symmetric level of steady-state labor devoted to R&D for each firm other than the leader is defined as l. With $(n - 1)$ R&D participants the economy-wide share of labor devoted to R&D is $(n - 1)l$. The labor market clears when

$$L = E/\lambda + (n - 1)l. \tag{5}$$

The Credit Sector

Firms finance research by borrowing from consumers at the risk free market rate $r(t)$. Through a well diversified portfolio investors can eliminate risk concerns. Arbitrage possibilities are eliminated when firms maximize expected returns from R&D.

FIGURE 1
Firm R&D Technology



STEADY-STATE EQUILIBRIUM

The steady-state perfect-foresight equilibrium examined here has the following properties:

1. Consumer expenditures remain constant over time, implying that the instantaneous interest rate equals the subjective discount rate.
2. Of the n firms with cutting edge R&D technology, there will be $(n-1)$ firms, which are non-producing followers, performing R&D. The remaining firm will be the sole producer of goods in the industry, but this firm performs no R&D.
3. Each R&D firm will choose the same level of R&D effort independent of industry or time period.
4. Prices and wages will be fixed across time and industry.

Existence of the Steady-state Equilibrium

Two equations determine the equilibrium for the model. The first equation is the "within-race R&D condition." This equation relates each individual firm i's R&D efforts during an R&D race to V, the reward each firm expects for winning the race, and $k = \Sigma_{j \neq i} h(l_j)$, the innovative effort each firm expects from its competitors in the race.

Each firm calculates the benefits it expects in an R&D race considering that it will only receive the reward for winning the race if it successfully innovates at time t and no other firm has been successful in innovating prior to t. The R&D labor choice made by the firm determines the firm's flow of R&D costs in the race. Each firm's expected costs for the entire R&D race equals its discounted flow of labor costs for the race. A non-leading firm i, investing in l_i units of R&D labor, earns expected R&D profits of[6]

(6) $$\text{Exp}[\Pi(l_i,k)]=[Vh(l_i) - l_i]/[\rho + k + h(l_i)].$$

In the symmetric Nash equilibrium, all competitors make the same R&D labor choices, that is $l_i=l$ for all $(n-1)$ identical participants in the R&D race. The R&D intensity choice which maximizes expected profits for each firm satisfies the "within-race R&D condition":

(7) $$V_W=[h(l) - lh'(l) + k + \rho]/[h'(l)(\rho + k)] = [(n-1)h(l) - lh'(l) + \rho]/\{h'(l)[\rho + (n-2)h(l)]\}.$$

This equation defines the relationship between the benefit firms expect for winning an R&D race and firm R&D efforts in the race provided the following assumption is satisfied.

Assumption 1 *For all $l \geqslant l'$, the form of R&D technology satisfies*

$$d[\partial \text{Exp}\Pi(l_i, k)/\partial l_i]dl \leqslant 0.$$

This assumption, also found in Lee and Wilde's [1980] analysis, ensures that the solution to equation (7) is stable. If the solution is unstable then a multilateral increase in each firm's R&D efforts will generate the desire for each firm to increase efforts further, generating an infinitely repeated series of further increases in each firm's R&D efforts.[7]

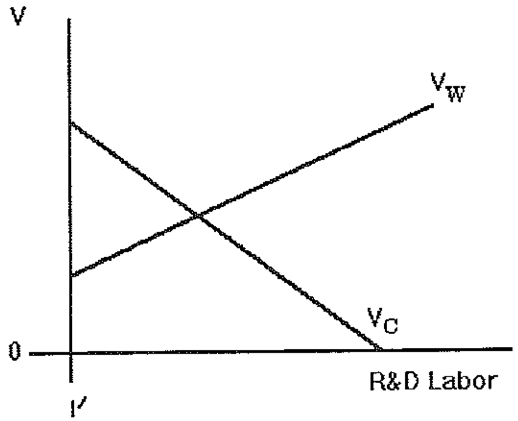
The "within-race R&D condition", equation (7), defines the R&D choices of firms, but only if the profits they expect from these R&D choice are non-negative. Substituting the expected benefit of winning an R&D race defined by the "within-race R&D condition," equation (7), into the expected R&D profit equation, equation (6), yields that for each firm

(8) $$EXP\Pi=[h(l) - lh'(l)]/[h'(l)(\rho + k)] = [h(l) - lh'(l)]/[h'(l)[\rho + (n-2)h(l)]].$$

These equilibrium expected R&D profits will be non-negative for each of the $(n-1)$ firms whenever the level of R&D labor defined by equation (7) for each firm i satisfies $l_i = l'$. Therefore, firms will never operate at a level where technology exhibits increasing returns to scale.

The second equation determining the steady-state equilibrium solution is the "cross-race R&D condition." This equation captures the relationship between R&D intensity in future R&D races and the expected benefits firms expect from success in the current race. Firms expect that if they win the current race, they will earn leading-firm profit flows until they are displaced by the innovator of the next generation product. In the steady state each firm is assumed to take the amount of R&D labor hired by all participants in all industries in the next R&D race as fixed at l. Given

FIGURE 2
The Steady-State Equilibrium



this steady-state assumption of perfect foresight, the winner of the current R&D race earns expected benefits equal to[8]

(9) $$V_C = [L - (n-1)l][\lambda - 1]/[\rho + (n-1)h(l)].$$

The "within-race R&D condition" and "cross-race R&D condition" determine both equilibrium firm R&D intensities and the benefits firms expect from winning R&D races in equilibrium. This solution is illustrated in Figure 2.

Given Assumption 1, firms choose greater R&D benefits during an R&D race when they expect a bigger prize for winning. Therefore, the "within-race R&D condition" is upward sloping in (l,V) space.[9] Furthermore, it is everywhere positive for $l \geq l'$, as firms only choose positive R&D efforts if the expected benefits from winning the R&D race are positive.

The "cross-race R&D condition" is downward sloping in (l,V) space.[10] This relationship is defined by two effects. First, with more resources devoted to R&D in the next R&D race, fewer resources will remain for the winner to use in the production of output during the next race. This reduces the flow profits each current R&D race participant expects if it successfully innovates. Second, with more R&D activity in the next R&D race each firm in the current race expects to retain any increase in market share it gets from winning the R&D race for a shorter period of time. Both effects decrease the expected value of winning a R&D race.

With the "within-race R&D condition" upward sloping and positive and the "cross-race R&D condition" downward sloping, a unique equilibrium will exist with firms choosing positive amounts of R&D labor provided $V_C(l') \geq V_W(l')$. This is assured by the following assumption:

Assumption 2 *L is sufficiently large so that*

$$L \geq [\rho + (n-1)h(l')]/[h'(l')(\lambda - 1)] + (n-1)l'.$$

When this assumption is met labor is sufficiently abundant for both profitable production and R&D.[11]

Proposition 1 *Given Assumptions 1 and 2, a unique steady-state equilibrium exists with firms earning non-negative expected profits from R&D.*

THE FREE-ENTRY EQUILIBRIUM

The free entry equilibrium is defined as the steady-state equilibrium in which expected profits from R&D are zero. The number of active firms with the ability to perform R&D in the free entry equilibrium is defined as n^*. Of these firms (n^*-1) will participate in each R&D race, with the state-of-the-art producer abstaining. When the number of firms active in each R&D race reaches (n^*-1), no further firms will wish to enter the R&D race as R&D is not profitable.

There are two cases of free entry equilibria — with initial increasing returns in R&D, and without. Without initial increasing returns, R&D spending initially generates very large marginal returns which decrease as R&D spending increases. It is easily seen from equation (8) that in this case firms will have an opportunity to earn positive profits as long as success by another firm in the industry is not instantaneous. The free entry number of firms in this case approaches infinity. If an initial range of increasing returns does occur, then R&D spending initially generates very small marginal returns, which increase as R&D spending increases, then decline again once the increasing returns are exhausted. As the number of firms is increased, the equilibrium value of firm R&D approaches l', the minimum profitable level of R&D spending. Given the within-race and cross-race R&D equations, equations (7) and (9), the free entry number of firms is finite and equals

(10) $$n^* = [Lh(l')(\lambda - 1) - l'\rho]/[\lambda h(l')l'] + 1.$$

Attention below is restricted to the case with initial increasing returns and finite entry.

COMPARATIVE STEADY-STATE ANALYSIS

The economy's labor endowment, the size of quality increases produced by successful R&D, consumer discount rates, and the number of firms participating in R&D races each affect the R&D choices firms make. A comparison of steady states explains how firms react to changes in each of these economic conditions.

When the economy is endowed with more labor resources, each firm will hire more R&D labor in each race. The current R&D race participants know that if the resource endowment grows, more labor will be available for production during the next race. With more output being produced in the next race, the profit flows that the winner of the current race (next period's producer) expects to earn are larger. This effect results in a shift to the right in the cross-race R&D curve, as the benefits a winner expects increase for every R&D effort level expected in the future. With an increase in the economy's resource endowment, both the equilibrium value of firm R&D effort and equilibrium benefits R&D race winners expect increase.

Each firm will also hire more R&D labor in each race when the size of potential innovations is larger. The current R&D race participants know that if the next innovation is relatively larger both the price markup and profit flows they will earn, if they win the current race, will increase. Because the benefits a winner expects increase for every given R&D effort level, this also shifts the cross-race R&D curve to the right. With an increase in the size of innovations the equilibrium value of firm R&D effort and equilibrium benefits R&D race winners expect both increase.

Firm R&D efforts will increase both when the economy's resource endowment increases and when the size of innovations increases. In both cases, with a constant number of firms, each choosing greater R&D intensity, industry innovations are expected to arrive at a more rapid rate.

An increase in the subjective discount rate will decrease firm R&D efforts. When the subjective discount rate increases, the within-race R&D curve will shift to the right. Although the expected benefits from R&D decrease because the value of the prize a firm expects to receive for winning a R&D race is discounted more heavily, the expected costs from R&D also decrease because the flow of expenditures during the R&D race are discounted more heavily. The fall in the marginal expected costs from R&D exceeds the fall in expected marginal benefits and firms wish to increase their R&D intensity. At the same time the cross-race R&D condition shifts to the left. Once a firm successfully innovates, a greater discount rate reduces the present discounted value of the flow of profits the winner expects and the expected value of the prize for winning the R&D race decreases. The cross-race effect dominates and any increase in the discount rate reduces the R&D efforts of firms in equilibrium.[12] As intuition would suggest, when society cares less for the future, present consumption increases and fewer resources are devoted to R&D investments with future payoffs.

Firm R&D efforts will decrease when the subjective discount rate increases. In this case, with a constant number of firms each choosing smaller R&D intensities, industry innovations are expected to arrive at a slower rate.

An increase in R&D participation will also reduce each firm's R&D efforts.[13] A combination of within-race and cross-race effects also produce this result. The within-race effects resulting from increased R&D race participation are positive and mirror the effects found in the Lee and Wilde model. With a constant expected benefit of winning and more participants in the R&D race, the expected marginal benefit of R&D for firms decreases, as it becomes less likely any one firm will be the first to innovate. At the same time the race is expected to end sooner, reducing expected marginal costs from R&D. The latter effect dominates and each firm increases its R&D effort for any given expected benefit of winning. The net effect is captured by a shift to the right in the within-race R&D curve which results in both a reduction in expected winner benefits and increased individual firm R&D effort.

The cross-race (or intertemporal) effects, though, dominate this relationship. These are the effects overlooked in the single episode models. Assuming R&D race participation increases in each period, current R&D race participants expect that in the next race fewer resources will remain for production of output. This reduces both the flow profits and total benefits winning firms expect. Second, assuming R&D race participation increases in each period, current R&D race participants expect innovations to arrive sooner. This reduces both the period of time a winner expects to receive leader profit flows (the leader's product will likely become obsolete quicker) and the benefit of winning an R&D race. Both factors shift the cross-race R&D condition to the left, reduce the equilibrium R&D effort chosen by each firm, and reduce the expected benefits winners receive in equilibrium.

The within-race effects are dominated by the cross-race effects and when R&D race participation rises each firm reduces its equilibrium R&D effort and the expected benefit to R&D race winners falls in equilibrium. That this result is driven by intertemporal effects is a clear indication that these effects are critical to understanding firm R&D behavior.

Proposition 2 *Given Assumptions 1 and 2, R&D firms will choose to hire less R&D labor whenever more firms participate in R&D races.*

When more firms participate in R&D races each firm does less R&D, lowering the instantaneous probability of success in the industry at any moment. However, more firms do R&D, increasing the industry-wide instantaneous probability of success. Above I showed that increased participation unambiguously decreases the expected benefit to winners of R&D races. Given that the equilibrium value of V declines, the value of V_C defined by the cross-race R&D condition will decline with the new participation level. We can check the following four possibilities against this result.

(i) $(n-1)l$ is non-increasing and $(n-1)h(l)$ is non-increasing as n increases.
(ii) $(n-1)l$ is non-decreasing and $(n-1)h(l)$ is non-increasing as n increases.
(iii) $(n-1)l$ is non-increasing and $(n-1)h(l)$ is non-decreasing as n increases.
(iv) $(n-1)l$ is non-decreasing and $(n-1)h(l)$ is non-decreasing as n increases.

Case (i) is ruled out because it cannot be the case that both $(n-1)l$ and $(n-1)h(l)$ both are non-increasing as n increases. Otherwise V_C, the value of V defined by the cross-race R&D condition, would be non-decreasing, contrary to what was proven above. By similar reasoning, case (ii) can be ruled out.[14] The remaining two possibilities both include a non-decreasing value of the industry-wide probability of success $(n\text{-}1)h(l)$. Further, ruling out cases (i) and (ii) rules out the possibility that the instantaneous probability of success in the industry remains fixed as n increases. Therefore, the industry-wide probability of success must strictly increase when participation increases and innovations must arrive at a faster rate.

Proposition 3 *Given Assumptions 1 and 2, the industry-wide instantaneous probability of success increases with participation. Thus the steady-state level of growth is strictly higher when more firms compete in R&D in each industry.*

WELFARE IMPLICATIONS OF THE MODEL

By definition, any steady-state equilibrium will consist of a constant number of firms participating in R&D at the same intensity in each industry across time. Taking the number of firms, n, in each industry as fixed and also taking the amount of R&D labor hired by each R&D race participant, l, as fixed, independence of R&D effort gives a time-invariant industry R&D parameter of $(n-1)h(l)$. Given this parameter and using the law of large numbers and properties of the Poisson distribution, consumers' steady state lifetime discounted utility is

$$U = [\ln E - \ln\lambda]/\rho + [(n-1)h(l)\ln\lambda]/\rho^2. \tag{11}$$

Combined with the economy's resource constraint, $E \leqslant [L-(n-1)l]$, this utility function can be used to analyze welfare implications of possible equilibria.

R&D resource commitments, which are determined by R&D participation rates and individual firm R&D efforts, affect both current and future consumption possibilities. These commitments affect future consumption possibilities by determining the rate of innovation. These effects show up in the second term of the lifetime utility function in equation (11) which depends directly on both participation and firm R&D efforts. R&D commitments affect current consumption through the resource constraint because R&D resource commitments determine the amount of resources that can be committed to producing consumption goods at any moment. These effects are captured in the first term in the lifetime utility function in equation (11) which depends on E, the consumer spending level determined by both participation and firm R&D efforts. Large R&D resource commitments increase future consumption at the expense of current consumption while small R&D resource commitments increase current consumption at the expense of future consumption. A social planner deciding how many resources to allocate to R&D must determine the proper balance between the two.

I examine the results of two possible social planning equilibria and compare these to the results of the model when entry is unrestricted. The first planning equilibrium allows the social planner to choose only the level of R&D effort of each firm, with the number of firms fixed at the free-entry level, n^*. The second planning equilibrium allows the social planner to choose the individual firm effort and the degree of participation in R&D in each industry.

In the first planning equilibrium, the social planner chooses only the level of R&D done by each firm, represented by l^{**}. Taking the number of firms as fixed at n^*, the social planner maximizes intertemporal utility subject to the resource constraint by choosing l^{**} to satisfy

$$[L-(n^*-1)l^{**}]h'(l^{**}) = \rho/\ln\lambda. \tag{12}$$

This equation implicitly defines the socially optimum R&D effort for each firm. In the free market each firm chooses an effort $l = l'$ which under free entry satisfies

$$[L-(n^*-1)l']h'(l')=[\rho+(n^*-1)h(l')]/(\lambda-1). \tag{13}$$

These two equations determine how the free market solution compares to the first planning solution.

When l' is substituted for l^{**} in Equation (12) the left-hand sides of both Equations (12) and (13) are equal to $[\rho+(n^*-1)h(l')]/(\lambda-1)$. Equation (12) will be satisfied with equality at l' provided the right-hand sides of both equations are equal; that is $\rho/\lambda + [Lh(l')]/[\lambda l'] = \rho/\ln(\lambda)$. In this case the free entry equilibrium and the social planning equilibrium will be equivalent. This determines a critical value of labor supply for which the free entry solution is socially optimal. This value is given by

$$L^C = [\rho/h'(l')](\lambda/\ln(\lambda)-1). \tag{14}$$

Whenever the resource endowment exceeds the critical level defined in Equation (14) the social planner will choose a larger R&D effort for each firm than occurs in the free entry equilibrium.[15] If the economy's resource endowment is below the critical value the social planner will choose a lower R&D effort for each firm than would occur in the free entry equilibrium.

In the second social planning equilibria the planner is free to choose both the effort of each firm, l^{**}, and the number of firms participating in R&D, n^{**}. To maximize the representative consumer's discounted utility subject to the resource constraint the social planner chooses l^{**} and n^{**} to satisfy both

$$[L-(n^{**}-1)l^{**}]h'(l^{**}) = \rho/\ln\lambda, \tag{15}$$

and

$$l^{**}/[L-(n^{**}-1)l^{**}] = [h(l^{**})\ln\lambda]/\rho. \tag{16}$$

Combining the two equations yields the efficient social level of individual firm R&D effort of $l^{**} = l'$. The planner's choice of effort will be the same as will occur in the unrestricted entry case. The optimal number of firms is then

$$n^{**} = 1 + [Lh(l')\ln\lambda - l'\rho]/[l'h(l')\ln\lambda]. \tag{17}$$

Comparing n^{**} to n^* from equation (10) we find that $n^{**} > n^*$ when $L > L_C$, $n^{**} = n^*$ when $L = L_C$ and $n^{**} < n^*$ when $L < L_C$.

Proposition 4 *Firms do too little, the socially optimal amount, or too much R&D as the labor force is greater than, the same as, or less than L_C, respectively.*

(i) *In the first planning case, where the planner is only able to select firm R&D efforts, firms choose to employ less, the same amount, or more labor than the planner would choose as the labor force is greater than, the same as, or less than L_C, respectively.*

(ii) *In the second planning case, where the planner is able to select both firm R&D efforts and participation rates, firms choose the same R&D effort level as a planner but fewer, the same, or more firms participate than the planner would choose as the labor force is greater than, the same as, or less than L_C, respectively.*

The differences between the free market and planning solutions result from differences between the private and social returns in the model.[16] First, firms fail to appropriate all of the increases in consumer welfare that accompany an innovation because firms are unable to set perfectly discriminating prices. Second, firms do not consider that by innovating they create positive externalities for competitors in the industry by creating an increase in the knowledge base for future R&D in the industry. Both effects, the "consumer surplus" effect and the "intertemporal spillover" effect, lead to free market solutions with less individual R&D than is socially optimal. The additional societal benefit over what the firm expects from increasing R&D efforts associated with both effects is $\ln(\lambda)/\rho$. Firms also ignore the profits they will "steal" from other firms when they successfully innovate. This "business stealing" effect pushes the free market solution to a level of individual R&D greater than the socially optimal level. The loss in societal benefit associated with this effect is $\lambda/[\rho + Lh'(l')]$. Which effects will be larger depend precisely on how large the labor supply endowment is relative to the critical value L_C. When the labor supply exceeds the critical value, L_C, the "consumer surplus" and "intertemporal spillover" effects will dominate the "business stealing" effect and welfare is raised by increasing firm efforts. When the labor supply falls short of the critical value, the "business stealing" effect dominates and welfare increases when firms reduce their R&D efforts.

CONCLUSION

Competition increases industry innovation rates; yet as demonstrated here it may reduce the individual R&D efforts of firms within industries. Consequently, policy makers narrowly focusing attention on individual firm R&D efforts will draw mistaken conclusions regarding the effects of competition. In order to avoid such mistakes, and design efficient R&D policy, planners must have a clear understanding of the forces driving innovation.

The analysis presented here contributes to this understanding of R&D markets by examining R&D technology characterized by decreasing returns at the firm level in a quality ladders model. This formulation allows an examination of the relationship between competition and R&D behavior, a relationship not well developed in previous quality ladders models. With decreasing returns R&D technology, individual firm behavior becomes important in determining the overall probability of success in the industry. The more firms that participate the more likely success is to occur. This suggests that policy makers, who are prevented from directly subsidizing R&D, can still increase growth rates through policies that encourage competition in R&D.

Particularly important in this relationship are dynamic characteristics of firm entry into R&D races, characteristics overlooked in single R&D race models. By understanding these intertemporal effects, policy makers will avoid the misinterpretations suggested above. The analysis here suggests that in order to evaluate R&D policy, planners must examine industry efforts, since focusing on the individual firms will lead to precisely the wrong conclusions.

While the model makes strides towards a clearer understanding of the R&D process, many areas of research remain. Relaxing the assumption of homogeneous R&D technology may give greater insight into the relationship between industry leaders and potential entrants. Imitation also plays an important part in firm R&D behavior, and the relationship between participation in R&D races and firm R&D behavior when imitation occurs warrants further study. However, what is clear from the model is that understanding individual firm R&D behavior is important to understanding technologically driven growth, and that understanding firm R&D behavior requires understanding intertemporal aspects of the relationships between market conditions and R&D behavior.

NOTES

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1. Both Grossman and Helpman[1991b] and Barro and Sala-i-Martin[1995] contain surveys of the empirical growth literature.
2. The quality ladders model was developed by Segerstrom, Anant, and Dinopoulos[1990], Aghion and Howitt[1992], and Grossman and Helpman[1991a]. Extensions of the model are found in Segerstrom[1991], Grossman and Helpman[1991b], and Barro and Sala-i-Martin[1995].
3. A model developed by Segerstrom[1995] contains industry-level decreasing returns to R&D, but firm-level R&D behavior remains indeterminate in Segerstrom's model. A second model by Thompson and Waldo[1993] looks at firm-level decreasing returns technology but in an environment of horizontally differentiated products.
4. Below I will show that in each industry, in the steady-state equilibrium, the quality leader in the industry sets the lowest quality-adjusted price and is the sole producer of goods.
5. A proof that for n sufficiently large, R&D will not be profitable for the state-of-the-art producer is available on request from the author. This is the case of interest here. For circumstances under which the "quality leader" will join R&D races see Zolnierek[1997] and Segerstrom and Zolnierek[1997].
6. $\int_{t=0\ldots\infty} V e^{-\rho t} h(l_i) e^{-h(l_i)t} e^{-kt} dt - \int_{t=0\ldots\infty} [\int_{s=0..t} l_i e^{-\rho s} ds](k+h(l_i)) e^{-(k+h(l_i))t} dt$ is the formal expression for the expected profits from R&D. Integrating this expression yields equation (6).
7. An appendix is available on request from the author with an explicit derivation of this restriction on technology. This appendix also demonstates that a broad class of technological forms meet the requirements of this condition, including the constant returns technology adopted in previous quality ladders models.
8. $V = \int_{t=0\ldots\infty} [\int_{s=0..t} E(\lambda - 1)/\lambda e^{-\rho s} ds](n-1) h(l) e^{-(n-1)h(l)t} dt$ is the formal expression for the expected prize for winning a R&D race. Integrating this equation and substituting for equilibrium spending as defined by the labor market equation, equation (5), produces equation (9).
9. $\partial V_W/\partial l = -[h''(l)[\rho(2n-3)h(l) + \rho^2 + (n-1)(n-2)h(l)^2] + (n-2)h'(l)^2[lh'(l) - h(l)]]/[h'(l)^2[\rho + (n-2)h(l)]^2]$ is positive for all $l \geqslant l'$.
10. $\partial V_C/\partial l = -[(\lambda - 1)(n-1)[\rho + Lh'(l) + (n-1)[h(l) - lh'(l)]]]/[\rho + (n-1)h(l)]^2$ is negative for all $l \geqslant l'$.
11. This requires that the labor resources remaining when firms each choose the minimum profitable R&D effort, l', are sufficiently large to make R&D at l' profitable. From the labor market clearing condition, equation (5), $L-(n-1)l' = E/\lambda$. Assumption 2 requires resources after R&D hiring to be sufficiently large that $E/\lambda \geqslant [\rho + (n-1)h(l')]/[h'(l')(\lambda - 1)]$. Rearranging and substituting $h(l')/l'$ for

h'(l') yields {[$E(\lambda - 1)/\lambda$]/[$\rho + (n - 1)h(l')$]}$h(l') - l' = Vh(l') - l' \geqslant 0$, which is precisely the condition for R&D to be profitable for each firm at l'.

12. A formal proof of these results is available on request from the author.
13. Proofs of this and the following results are also available on request from the author.
14. If (ii) is true then, defining l as an implicit function of n, $d[(n - 1)l]/dn = l + (n - 1)dl/dn \geqslant 0$ and $d[(n - 1)h(l)]/dn = h(l) + (n - 1)h'(l)dl/dn \leqslant 0$, where dn is strictly positive and dl/dn is strictly negative. Then $l \geqslant -[(n - 1)/l][dl/dn] \Rightarrow -[h(l)(n - 1)/l - (n - 1)h'(l)]dl/dn \leqslant 0 \Rightarrow -(n - 1)[h(l)/l - h'(l)]dl/dn \leqslant 0$. In equilibrium $h(l)/l > h'(l)$, for $l > l'$ so case (ii) cannot occur.
15. If the resource endowment exceeds this critical value then $\rho/\lambda + [Lh(l')]/[\lambda l'] > \rho/\log(\lambda)$ and substitution of l' for l^{**} into Equation (12) will not produce equality. In this case, because the left-hand side of Equation (12) exceeds the right-hand side with the substitution of l' for l^{**}, and because the left-hand side is decreasing in l, a value l^{**} greater than l' is necessary to satisfy equation (12).
16. The analysis below follows the analysis of the model with constant returns technology found in Grossman and Helpman[1991b].

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