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**R&D Competition in an Asymmetric
Cournot Duopoly: The Welfare
Effects of Catch-Up by the Laggard Firm**

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R&D Competition in an Asymmetric Cournot Duopoly: The Welfare Effects of Catch-Up by the Laggard Firm

Abstract

The substantial within-industry variation in firm productivity typically observed in the data suggests that there is ample scope for catch-up by laggard firms. We analyse the normative effects of such catch-up. In the short run, where firms' process technologies are fixed, catch-up can reduce social welfare if the initial unit-cost gap between firms is sufficiently large (the Lahiri/Ono effect). However, in the long run, where firms invest in process R&D to maximize profits, social welfare jumps upwards following catch-up if it causes the major firm's R&D spending lead to grow. Both qualitative insights appear quite general.

Keywords: asymmetric duopoly, catch-up, social welfare, process R&D.

JEL classifications: D61, L13, O33.

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1 Introduction

Our starting-point is the stylized fact that within-industry variation across firms in productivity is typically very large. For the UK, Haskel and Martin (2002) examine productivity dispersions within manufacturing industries over 1980-2000. They show that, in 2000, the average labour productivity gap in manufacturing industries between the 90th and 10th percentile plants was above 5 to 1. The same gap in terms of total factor productivity was about 1.6 to 1. Moreover, Haskel and Martin show that, if anything, the typical productivity spread in UK manufacturing increased between 1980 and 2000.

Oulton (1998) provides two specific senses in which the productivity spreads within UK manufacturing industries are “large.” First, using company accounts data for the whole UK economy, Oulton shows that, in 1993, dispersion across firms in labour productivity was about 50% higher than in weekly earnings. Second, Oulton shows that about three quarters of labour-productivity dispersion across firms is due to differences in productivity between firms in the same narrowly-defined (i.e., 4-digit) industry. Moreover, although Haskel and Martin restrict their attention to UK manufacturing, the stylized fact that within-industry productivity dispersion is “large” appears to be robust across both other broad sectors of the UK economy (e.g., services¹) and other countries (e.g., Dwyer, 1998, on US textile industries).

These large within-industry productivity gaps suggest that there is ample scope for laggard firms to catch up with industry leaders. In this paper, we analyse the welfare effects of catch-up by laggards. We introduce a distinction in logical time between the short and long runs, and we examine the effects of catch-up over those two horizons. In the *short run*, firms’ process technologies are given, and catch-up moves laggards towards the static industry technology frontier, whose position is determined by the industry leader’s technology. However, in the *long run*, the industry’s technology frontier can move outwards as a result of firms’ R&D investment decisions, which are then endogenously determined to maximize profits. Therefore, our notion of short vs. long run has its counterpart in the familiar normative concepts of static vs. dynamic efficiency (Tandon, 1984; Qiu, 1997).

In reality, catch-up by laggards can occur for a variety of reasons – for example, as a result of purposive actions by firms and governments, and due to “natural” processes

¹ Oulton (1998) reports that the within-industry dispersion across firms in labour productivity is around 40% *lower* in UK manufacturing than elsewhere in the UK economy.

of technology diffusion and imitation. One of the stated reasons why countries like the UK have been so keen to host foreign direct investment (FDI) is that foreign-owned plants typically exhibit higher labour productivity than domestically-owned ones within the same industry (Griffith *et al.*, 2004). To the extent that domestic/foreign TFP differences underlie these observed labour productivity gaps, host governments hope that inward FDI will lead to foreign-to-domestic productivity spillovers, which improve the performance of domestic firms (Görg and Greenaway, 2004). Moreover, independently of the foreign sector, leader-to-laggard spillovers can occur over time within an industry as laggards learn from leaders and technology diffuses (Malerba, 1992). Finally, the deliberate actions of firms can contribute to bringing laggards up to date with industry best practice. Joint ventures, technology licensing, and trade associations are all examples of mechanisms through which this can occur, and they are all empirically common.

Because our primary concern is not the incentives of governments and firms to foster catch-up by laggards, we do not model the catch-up process and its associated costs explicitly.² Rather, we take a degree of catch-up as given and investigate its normative effects.³ To study the effects of movement by minor firms towards the technology frontier, we model R&D competition in a two-stage duopoly. In the first stage, the firms choose their investment levels in process R&D, and in the second, they compete à la Cournot on the product market. The firms are asymmetric both initially (because their initial unit costs differ, as a result of pre-game history) and in terms of their investment opportunities in process R&D, which is a binary choice where the firms' R&D fixed costs and innovation sizes in general differ. Our equilibrium concept is subgame perfection, and we restrict the inter-firm unit-cost gap to ensure that interior Cournot equilibria always exist. Our modelling structure therefore extends the familiar two-stage analyses of R&D competition (i.e., process R&D choices, followed by market competition) by relaxing the conventional assumptions of initially symmetric firms and symmetric process R&D opportunities across firms.⁴ Given the substantial within-industry productivity spreads typically observed in

² For a simple analysis of how foreign-to-domestic spillovers affect foreign firms' inward FDI incentives, and a discussion of possible spillover channels, see Ferrett (2005).

³ Our welfare standard is "social welfare," the unweighted sum of industry profits and consumer surplus. Therefore, our results will have implications for the willingness of a benevolent government to promote catch-up. Obviously, if catch-up reduces social welfare then, even with costless policy intervention, it should not be promoted.

⁴ Important papers in that literature that use these symmetry assumptions include Brander and Spencer (1983), d'Aspremont and Jacquemin (1988), Kamien *et al.* (1992), Suzumura (1992), and Leahy and Neary

the data, and discussed at the outset, we argue that this represents an important advance towards realism.⁵ Our model complements that of Boone (2001), who analyses the effect of marginal-cost asymmetries between firms on their willingness to bid for the patent on a process innovation, by allowing both firms to innovate simultaneously.⁶

We begin by analysing the consequences for social welfare of catch-up by the laggard firm in the short-run case where firms' process technologies are fixed. Here, reducing the laggard firm's unit cost has an intuitive impact on the individual components of social welfare. Consumers and the laggard firm itself both gain, but the low-cost leading firm loses. However, when these effects are aggregated together, social welfare falls if the unit-cost gap between the firms is sufficiently large.⁷ The intuition for this perverse effect is that, due to strategic substitution on the product market in Cournot competition, the laggard firm steals business from the leader when its unit cost falls, which is a socially inefficient redistribution of initial production. If the inter-firm unit-cost gap is sufficiently large, then the increased production costs on the output so redistributed can drag overall social welfare downwards.

Turning to the long run, where the firms choose their process R&D levels before Cournot competition, the normative effects of catch-up are more complex. If slightly cutting the minor (or laggard) firm's unit cost induces a change in equilibrium R&D decisions, then social welfare changes discretely (because process R&D investment itself is a discrete variable). If catch-up by the minor firm causes (via changes in equilibrium R&D behaviour) the major firm's R&D spending lead over its rival to grow, then social welfare jumps upwards.⁸ In this case, *reducing* the initial unit-cost gap between the

(1997).

⁵ Mills and Smith (1996) make the important point that an asymmetric game is *unnecessary* to generate asymmetric equilibria and explain asymmetric observations. However, our model *assumes* asymmetries between firms in initial conditions (accumulated R&D stocks) and R&D choice sets for two reasons. First, such asymmetries appear empirically significant. Second, it seems reasonable to assume that accumulated R&D stocks ("initial conditions") are largely independent of the (possibly small) catch-up "intervention." Most obviously, the catch-up under analysis could be unanticipated. However, even if it was (at least partially) foreseen, the catch-up "intervention" may not have affected R&D investments in the past – e.g., because Knightian uncertainty (as opposed to risk) shortens firms' "objective" planning horizons. (See Rölller and Sinclair-Desgagné, 1996, for discussion of the causes of inherited asymmetries.)

⁶ Our paper addresses similar questions within the "R&D competition" literature to those that Boone considers within the "patent race" tradition.

⁷ Lahiri and Ono (1988) first highlighted this effect explicitly, and it plays a role in the welfare analysis of trade liberalisation within Brander and Krugman's (1983) "reciprocal dumping" model. See also Zhao (2001).

⁸ Specifically, the major firm's R&D spending lead rises between equilibria if it takes up R&D plans

firms raises social welfare discretely because it *widens* the equilibrium unit-cost gap. Because of strategic substitution in outputs, this widening provokes an efficient reallocation (minor-to-major) of initial production levels. The fact that a larger unit-cost gap can increase social welfare was highlighted by Salant and Shaffer (1999). Our analysis goes a step further by showing that, with discrete process R&D investments, the initial and equilibrium unit-cost gaps are inversely related to each other.

We also explore, in the long-run case, the monotonicity properties of equilibrium social welfare in the minor firm’s initial unit cost. We are interested in exploring conditions under which equilibrium social welfare is “well-behaved” (i.e. monotonically decreasing in the minor firm’s initial unit cost), so that catch-up is always beneficial. We show that this requires that the minor firm’s R&D fixed cost be sufficiently small. In this case, the minor firm chooses to invest in R&D for all the (high) levels of its initial unit cost where social welfare would otherwise be upward-sloping, and thus the equilibrium social welfare function is well-behaved.

When the fact that, in a short-run context, helping minor firms could cut social welfare was first pointed out (Lahiri and Ono, 1988), the observation was used to rationalize the industrial policies pursued by the Japanese Ministry of International Trade and Industry (MITI) in the postwar period, which often favoured major firms over minor ones. An example was MITI’s practice of granting major firms better access to new (often imported) technologies, thus widening the gap between leaders and laggards (Lahiri and Ono, 1988, p. 1201).⁹ Such interventionist industrial policies are now much less popular with governments, and the predominant policy focus is on fostering “competition” (DTI, 2001). Our analysis also highlights the potential long-run gains from intensified competition, although the mechanism is perhaps unexpected. Intensifying competition by helping minor firms and narrowing the initial productivity gap can substantially boost long-run (equilibrium) social welfare if it causes the major firm’s R&D spending lead to grow and thereby widens the long-run productivity gap.

The remainder of the paper is organized as follows. The next section formally describes our two-stage game of R&D competition and defines our welfare measures. In section 3 we present the game’s subgame perfect equilibria. Sections 4 and 5 analyse, respectively, and/or the minor firm abandons them.

⁹ In a similar vein, Eatwell (1982, pp. 76-7) describes the purposive promotion of major firms by the French Commissariat Général du Plan during the same period.

the welfare effects of catch-up when the major firm's R&D is cheap and costly. Finally, section 6 concludes.

2 Model

We analyse R&D competition in a linear Cournot duopoly where the firms' cost structures are asymmetric using the following two-stage game of complete information. In *stage one*, the duopolists simultaneously and irreversibly choose whether to invest in process R&D (R) or not (N). By investing in R&D, firm $i \in \{1, 2\}$ obtains a unit cost of c_{iR} for a sunk cost of F_i . If i does not undertake R&D, its unit cost remains at its initial level of $c_{iN} > c_{iR}$. Therefore, in stage 1, firm i chooses between two pairs of unit (or marginal) and sunk costs, $(c_{iN}, 0)$ and (c_{iR}, F_i) , where the latter can be thought of as the installation of a new machine.¹⁰ We assume that c_{iR} and c_{iN} are independent, so varying c_{iN} alters the *size* of the process innovation.¹¹

In *stage two*, the duopolists compete à la Cournot on the market for a homogeneous good with inverse demand

$$p = 1 - (q_1 + q_2).$$

There are two principal justifications for our assumption of homogeneous products. First, given that we believe our qualitative insights will readily generalize to the case of differentiated products, it keeps our analysis mathematically straightforward.¹² Second, empirical evidence (Oulton, 1998) suggests that most of the variation across plants in total factor productivity (TFP) is within-industry, rather than between-industry. This is perhaps surprising, but it makes our assumption that producers of the same good face different R&D possibilities and costs plausible.¹³

We solve the game backwards to isolate its subgame perfect Nash equilibria in pure strategies. To avoid extensive and unrewarding taxonomy, we make two assumptions on

¹⁰ Note that this *discrete* formulation of the R&D decision is consistent with an underlying *continuous* R&D investment variable if the firm optimally chooses corners – e.g., if firm i chooses R&D investment level $x_i \in [0, 1]$, marginal cost equals $c_{iN} - (c_{iN} - c_{iR})x_i$, and R&D costs x_i .

¹¹ This assumption means that potential innovations are independent of the initial productivity dispersion in the industry.

¹² Although our qualitative results survive with differentiated products, *quantitatively* they will be weakened because a key mechanism behind our results is strategic substitution in the product market.

¹³ Moreover, the assumption of homogeneous goods facilitates straightforward comparison with the Lahiri/Ono (1988) analysis. Our qualitative results readily generalize to the case where $p = a - b(q_1 + q_2)$.

the marginal cost parameters. First, we assume *nondrastic* process innovations.¹⁴ This restricts the spread of marginal costs and requires

$$\frac{1}{2}(1 + c_{1R}) > c_{2N} \quad \text{and} \quad \frac{1}{2}(1 + c_{2R}) > c_{1N},$$

where the LHS's are monopoly prices following R&D, so the conditions ensure that either firm's monopoly price under R exceeds its rival's initial marginal cost. Second, we shall assume throughout that $c_{2N} \geq c_{1N}$, so that, initially, 1 is the "major" firm and 2 the "minor" one. This assumption entails no loss of generality. It merely excludes cases that are distinguished only by firm labelling. We denote firm i 's variable profits in Cournot equilibrium by $\pi(c_i, c_j)$, so

$$\pi(c_i, c_j) = \frac{1}{9}(1 - 2c_i + c_j)^2.$$

Using this notation, our game's payoff matrix is

[FIG. 1 HERE]

We shall define social welfare as the unweighted sum of profits and consumer surplus, where the latter is given by

$$S(c_i + c_j) = \frac{1}{2}(q_1 + q_2)^2 = \frac{1}{18}(2 - [c_i + c_j])^2$$

at an interior Cournot equilibrium. S is increasing and strictly convex in $(q_1 + q_2)$: a given rise in industry output (i.e. a given fall in p) is more valuable to consumers, the larger is the initial output that the price fall is spread over.

3 Preliminary results

Fig. 2 plots the game's subgame perfect equilibria in (F_1, F_2) -space. The comparative statics are intuitive: increasing a firm's sunk cost of R&D makes it less likely to undertake R&D. The inter-regional boundaries are defined as follows:

$$\begin{aligned} F_{1R}^* &= \pi(c_{1R}, c_{2R}) - \pi(c_{1N}, c_{2R}) = \frac{4}{9}(c_{1N} - c_{1R})[1 + c_{2R} - (c_{1N} + c_{1R})] \\ F_{1N}^* &= \pi(c_{1R}, c_{2N}) - \pi(c_{1N}, c_{2N}) = \frac{4}{9}(c_{1N} - c_{1R})[1 + c_{2N} - (c_{1N} + c_{1R})] \\ F_{2R}^* &= \pi(c_{2R}, c_{1R}) - \pi(c_{2N}, c_{1R}) = \frac{4}{9}(c_{2N} - c_{2R})[1 + c_{1R} - (c_{2N} + c_{2R})] \\ F_{2N}^* &= \pi(c_{2R}, c_{1N}) - \pi(c_{2N}, c_{1N}) = \frac{4}{9}(c_{2N} - c_{2R})[1 + c_{1N} - (c_{2N} + c_{2R})] \end{aligned}$$

¹⁴ i.e., that all four possible Cournot equilibria, one for each possible pair of marginal costs, are interior.

[FIG. 2 HERE]

F_{iR}^* (F_{iN}^*) is firm i 's gain in variable profits from investing in R&D when its rival chooses R (N). $F_{iN}^* > F_{iR}^*$ because by investing in process R&D a firm's rival becomes a tougher competitor, which reduces the rent available on the product market to fund the firm's own R&D effort.¹⁵ Note that we cannot in general say whether $F_{1R}^* \geq F_{2R}^*$ or $F_{1N}^* \geq F_{2N}^*$.¹⁶

We are interested in the normative effects of “helping” firm 2 by reducing c_{2N} . We start by ignoring the endogenous R&D aspect and focus on the (N, N) case. The industry's technology frontier is then represented by c_{1N} , and catch-up reduces c_{2N} towards it. Social welfare is given by

$$W(N, N) = \pi(c_{1N}, c_{2N}) + \pi(c_{2N}, c_{1N}) + S(c_{1N} + c_{2N}).$$

The key point to note is that $W(N, N)$ is *not* decreasing in c_{2N} on the whole interval of c_{2N} that is consistent with interior Cournot equilibria.¹⁷ In fact, $W(N, N)$ is U-shaped in c_{2N} .¹⁸ If the gap $(c_{2N} - c_{1N})$ is sufficiently large, then increasing c_{2N} increases social welfare – or, equivalently, “helping minor firms reduces welfare” (Lahiri and Ono, 1988). This result seems paradoxical, and it arises because the firms' outputs are strategic substitutes in our linear Cournot model. Cutting c_{2N} leads to a rise in q_2 and a (smaller) fall in q_1 . The individual components of social welfare are affected as one would expect: π_1 falls, π_2 rises, and S rises (because $q_1 + q_2$ rises). However, a part of industry production is redistributed inefficiently from firm 1 to firm 2 (major-to-minor) and if the gap $(c_{2N} - c_{1N})$ is sufficiently large, this inefficient redistribution can drag total social welfare downwards.¹⁹

Therefore:

¹⁵ Therefore, firm i 's dominant strategy is R if $F_i < F_{iR}^*$ and N if $F_i > F_{iN}^*$. If $F_i \in [F_{iR}^*, F_{iN}^*]$, then i optimally chooses the opposite to its rival. In the central square in Fig. 2, we have a game of chicken where either firm prefers the equilibrium where it does the R&D.

¹⁶ Two cases where ranking *is* possible deserve mention, however. First, if $c_{1R} = c_{2R}$ (i.e., R&D moves both firms onto the new technology frontier), then $F_{2R}^* > F_{1R}^*$ and $F_{2N}^* > F_{1N}^*$ for all $c_{2N} \in (c_{1N}, (1 + c_{1R})/2)$. Second, if $c_{1N} - c_{1R} = c_{2N} - c_{2R}$ (i.e., common innovation *size* across firms), then $F_{1R}^* > F_{2R}^*$ and $F_{1N}^* > F_{2N}^*$ for all $c_{2N} > c_{1N}$.

¹⁷ i.e. $c_{2N} \in (c_{1N}, \frac{1}{2}(1 + c_{1N}))$

¹⁸ See, for example, the plot of $W(N, N)$ in Fig. 4.

¹⁹ Despite our focus on Cournot competition, we would obtain qualitatively identical results under Bertrand competition with differentiated products. In that case, helping the minor firm will push both firms' prices downwards (strategic complementarity), benefiting the minor firm and consumers but harming the major firm. However, the minor firm's *relative* price will also fall, which will cause an inefficient

Proposition 1 (Lahiri and Ono, 1988): In an asymmetric, linear Cournot duopoly with both firms active in equilibrium, social welfare is U-shaped in the minor firm’s unit cost. Thus, catch-up by the laggard firm might reduce social welfare.

We characterize Proposition 1 as a *short run* result because it holds the firms’ R&D choices fixed. In the *long run*, firms’ R&D investments are variable, and we need to consider the effects of reducing firm 2’s initial unit cost, c_{2N} , on R&D investment patterns. For any pair of R&D costs (F_1, F_2) in Fig. 2, reducing c_{2N} will shift inwards all the inter-regional boundaries except F_{1R}^* , which is independent of c_{2N} . The possibility therefore arises that, for given (F_1, F_2) , cutting c_{2N} may alter equilibrium R&D decisions. Firm 2’s gains from R&D, F_{2R}^* and F_{2N}^* , both fall when c_{2N} falls because the *size* of the process innovation that R&D investment grants it falls – recall that, by assumption, c_{2R} is independent of c_{2N} . However, F_{1R}^* is independent of c_{2N} because when firm 2 undertakes R&D, technology c_{2N} is eliminated from production. Finally, F_{1N}^* also falls when c_{2N} falls. This reflects the fact that, with lower c_{2N} , 1’s output is smaller in Cournot equilibrium for either of 1’s R&D decisions. Therefore, the *value* of a given process innovation to 1, innovation size spread over equilibrium output, falls when c_{2N} falls.²⁰

With endogenous R&D decisions, there are two distinct cases of catch-up by firm 2 to consider, “small” and “large” F_1 . Formally, the distinction depends on whether $F_1 \geq F_{1R}^*$, where F_{1R}^* is independent of c_{2N} . Economically, it is the distinction between the case where firm 1 always undertakes R&D and that where 1’s R&D decision is contingent on 2’s.

4 Major firm’s R&D is cheap ($F_1 < F_{1R}^*$)

If $F_1 < F_{1R}^*$, where F_{1R}^* is independent of c_{2N} , then 1’s dominant strategy is to invest in R&D. Therefore, there are two possible subgame perfect equilibria (see Fig. 2): (R, R) for $F_2 < F_{2R}^*$, and (R, N) for $F_2 > F_{2R}^*$. The switchpoint, where firm 2 changes its R&D

reallocation of initial production (major to minor). Likewise, we conjecture that Propositions 2 and 3 below will also generalize to Bertrand competition with differentiated products.

²⁰ Our assumption of nondrastic process innovations is crucial for $\partial F_{1N}^*/\partial c_{2N} > 0$. If 1’s innovation were *drastic*, we would get $\partial F_{1N}^*/\partial c_{2N} < 0$ because 1’s profits in (R, N) would be independent of c_{2N} . Therefore, intensified competition weakens (strengthens) the incentive to invest in nondrastic (drastic) process innovations. This observation has implications for the impact of competition on chosen innovation *size* (drastic vs. nondrastic) and, perhaps, for the distinction between Schumpeter Mark I and II (Nelson and Winter, 1982; Breschi *et al.*, 2000).

decision, occurs at $F_2 = F_{2R}^*$, or²¹

$$c_{2N} = \alpha = \frac{1}{2} \left(1 + c_{1R} - 3\sqrt{\pi(c_{2R}, c_{1R}) - F_2} \right).$$

If $c_{2N} = \alpha$, then firm 2 is indifferent between (R, R) and (R, N) . If $c_{2N} > \alpha$, then firm 2 strictly prefers (R, R) to (R, N) and vice versa. *Thus, $c_{2N} > \alpha$ is equivalent to $F_2 < F_{2R}^*$.* (Clearly, if $F_2 = 0$, then $\alpha = c_{2R}$; otherwise, $\alpha > c_{2R}$.²²)

Fig. 3 below plots social welfare in the two equilibria, $W(R, R)$ and $W(R, N)$, as functions of c_{2N} , where²³

$$\begin{aligned} W(R, R) &= \pi(c_{1R}, c_{2R}) - F_1 + \pi(c_{2R}, c_{1R}) - F_2 + S(c_{1R} + c_{2R}) \\ W(R, N) &= \pi(c_{1R}, c_{2N}) - F_1 + \pi(c_{2N}, c_{1R}) + S(c_{1R} + c_{2N}) \end{aligned}$$

[FIG. 3 HERE]

$W(R, R)$ is independent of c_{2N} because if firm 2 invests in R&D, technology c_{2N} is eliminated from production. $W(R, N)$ is U-shaped in c_{2N} for the reasons underlying Proposition 1 above. There are two key features of Fig. 3. First, $W(R, N) > W(R, R)$ whenever (R, N) is the equilibrium. This property is robust to changes in the cost parameters.²⁴

Lemma 1: Assume that $F_1 < F_{1R}^*$ and $c_{2R} > c_{1R}$. $W(R, N) > W(R, R)$ whenever (R, N) is the unique subgame perfect equilibrium, which requires $F_2 > F_{2R}^*$ or $c_{2N} \in (c_{2R}, \alpha)$.

Proof: If $c_{2N} < \alpha$, then firm 2 prefers (R, N) to (R, R) , so a sufficient condition for $W(R, N) > W(R, R)$ is $\pi(c_{1R}, c_{2N}) + S(c_{1R} + c_{2N}) > \pi(c_{1R}, c_{2R}) + S(c_{1R} + c_{2R})$.

This condition ensures that the rest of society (i.e., firm 1 plus consumers) prefers

²¹ $F_2 = F_{2R}^*$ yields a quadratic in c_{2N} , but only the smaller root is compatible with interior Cournot equilibria (the turning point of F_{2R}^* is at $c_{2N} = (1 + c_{1R})/2$).

²² By our assumptions on the unit cost parameters, c_{2N} is restricted to the interval $(\max\{c_{1N}, c_{2R}\}, \frac{1}{2}(1 + c_{1R}))$. In order to ensure that α always lies within this interval, we require $F_2 < \pi(c_{2R}, c_{1R})$, where the RHS is the value of F_{2R}^* when $\pi(c_{2N}, c_{1R}) = 0$ at $c_{2N} = (1 + c_{1R})/2$. For clarification, see the plot of critical F -values in the appendix.

²³ In Fig. 3, we set $c_{1R} = 0$ so the monopoly price $(1 + c_{1R})/2 = 0.5$; $c_{1N} = 0.1$; and $c_{2R} = 0.15$. Therefore, $F_{1R}^* = 0.047 > F_1 = 0.025$; $\pi(c_{2R}, c_{1R}) = 0.054 > F_2 = 0.025$; and $\alpha = 0.24$.

²⁴ In Lemma 1, the condition $c_{2R} > c_{1R}$ means that the laggard cannot leap-frog over the leader if the leader invests in R&D. Given the large within-industry variation in TFP across firms typically observed in the data, this seems plausible.

(R, N) . Iff $c_{2R} > c_{1R}$, then the sufficient condition holds for all $c_{2N} > c_{2R}$: LHS = RHS at $c_{2N} = c_{2R}$, and $\partial\text{LHS}/\partial c_{2N} > 0$ for all $c_{2N} > c_{1R}$.

In particular, Lemma 1 means that $W(R, N) > W(R, R)$ at $c_{2N} = \alpha$ where firm 2 is indifferent between R and N , so there is a jump upwards in social welfare when c_{2N} is pushed below α and firm 2 abandons its R&D plans. This property is purely driven by the welfare effects on the rest of society (because firm 2 itself is indifferent). It arises because of the strategic substitution in Cournot equilibrium, and consequent *efficient* redistribution of initial production levels (minor-to-major), that is caused by a rise in firm 2's unit cost from c_{2R} to c_{2N} when 2 abandons R&D.

The second noteworthy feature of Fig. 3 is an artefact of the chosen cost parameters: the switchpoint α lies to the left of the turning point of $W(R, N)$, which implies that catch-up by firm 2 *always* increases social welfare. This second property requires that F_2 be sufficiently small. (To understand this, note that the curvature of a given $W(\cdot, \cdot)$ function is independent of the sunk costs F_1, F_2 because they enter social welfare additively. However, the switchpoints between different R&D regimes in equilibrium *do* vary with the sunk costs of R&D. Therefore, by reducing F_2 we strengthen firm 2's R&D incentive and eventually push α to the left of the turning point in $W(R, N)$.²⁵)

Proposition 2 sums up our results in this section:

Proposition 2: Assume an asymmetric, linear Cournot duopoly where the minor firm's (discrete and nondrastic) process R&D decision is endogenous. (a) Whenever the minor firm chooses not to invest in R&D in equilibrium, this leads to higher social welfare. Thus, catch-up by the minor firm increases social welfare discretely if it prompts the minor firm to abandon its R&D plans. (b) If the minor firm's R&D is sufficiently cheap, then catch-up always increases social welfare so the Lahiri/Ono effect is never observed.

It is useful to reflect on the mechanism behind Proposition 2. If it causes the minor firm to abandon its R&D plans, then *reducing* the initial unit-cost gap between the firms by cutting c_{2N} raises equilibrium social welfare discretely because it *widens* the equilibrium unit-cost gap and thereby provokes an efficient reallocation of initial production levels.

²⁵ Reducing F_2 also increases $W(R, R)$ relative to $W(R, N)$ in Fig. 3, but Lemma 1 always applies.

Overall, this section has achieved two things. First, we have shown that catch-up by firm 2 causes a jump upwards in social welfare at the point where 2 shelves its R&D plans as firm 1 grows at the expense of 2 on the product market. Second, over intervals where the firms' optimal R&D decisions are unchanging (so social welfare varies continuously with the minor firm's unit cost), we have weakened the Lahiri/Ono result on the conditions under which "helping" the minor firm is harmful. With endogenous R&D decisions, social welfare can increase in the minor firm's unit cost only if its sunk cost of R&D (and therefore α) is sufficiently large.

In the next section we consider the case of costly major-firm R&D.

5 Major firm's R&D is costly ($F_1 > F_{1R}^*$)

If $F_1 > F_{1R}^*$, where (to repeat) F_{1R}^* is independent of c_{2N} , then there are three possible subgame perfect equilibria: (N, R) , (R, N) , and (N, N) . To get a handle on the taxonomy, we begin by tying down the equilibria at the extremes: $c_{2N} = c_{2R}$ and $c_{2N} = (1 + c_{1R})/2$ (where the RHS is firm 1's monopoly price following R&D). For any (F_1, F_2) with $F_1 > F_{1R}^*$, the subgame perfect equilibrium when $c_{2N} = c_{2R}$ is (N, N) .²⁶ At the top end, where $c_{2N} = (1 + c_{1R})/2$, so firm 2 is pushed out of the market if 1 innovates alone, we shall assume $F_1 < F_{1N}^*$ and $F_2 < F_{2R}^*$ so the subgame perfect equilibrium is (N, R) (see Fig. 2).

Starting at $c_{2N} = (1 + c_{1R})/2$ with an equilibrium of (N, R) , reducing c_{2N} shifts F_{1N}^* , F_{2R}^* and F_{2N}^* all inwards as the returns to innovation fall. Developing the notation from the previous section, we define two critical levels of c_{2N} to make firm 2 indifferent between N and R :

$$\begin{aligned} F_2 &= F_{2R}^* \text{ at } c_{2N} = \alpha = \frac{1}{2} \left(1 + c_{1R} - 3\sqrt{\pi(c_{2R}, c_{1R}) - F_2} \right) \\ F_2 &= F_{2N}^* \text{ at } c_{2N} = \beta = \frac{1}{2} \left(1 + c_{1N} - 3\sqrt{\pi(c_{2R}, c_{1N}) - F_2} \right) \end{aligned}$$

where (see plot in appendix)

$$\frac{1}{2} (1 + c_{1R}) \underbrace{\quad}_{\text{I}} \underbrace{\quad}_{\alpha} \underbrace{\quad}_{\text{II}} \underbrace{\quad}_{\beta} \underbrace{\quad}_{\text{III}} c_{2R}.$$

α was introduced in the previous section; and $c_{2N} > \alpha$ is equivalent to $F_2 < F_{2R}^*$. In similar manner, $c_{2N} > \beta$ is equivalent to $F_2 < F_{2N}^*$, and it implies that firm 2 strictly prefers (N, R) to (N, N) .

²⁶ Of course, if $c_{2N} = c_{2R}$, then $F_{1N}^* = F_{1R}^*$ and $F_{2N}^* = F_{2R}^* = 0$ – 1's incentive to innovate is independent of 2's choice, and 2 has no incentive to invest in R&D.

The sequence of subgame perfect equilibria as c_{2N} falls from $(1 + c_{1R})/2$ to c_{2R} depends on which interval (I, II or III in the ranking above) a third critical level of c_{2N} , γ , occupies. At $c_{2N} = \gamma$, $F_1 = F_{1N}^*$ and firm 1 is indifferent between (R, N) and (N, N) . Therefore,

$$\gamma = \frac{9F_1}{4(c_{1N} - c_{1R})} + c_{1N} + c_{1R} - 1$$

where $c_{2N} > \gamma$ is equivalent to $F_1 < F_{1N}^*$. As c_{2N} falls, there are three possible sequences of equilibria to consider (again, see plot in appendix):²⁷

Sequence I ($\gamma > \alpha > \beta$) : $(N, R) \xrightarrow{\beta} (N, N)$

Sequence II ($\alpha > \gamma > \beta$) : $(N, R) \xrightarrow{\alpha} \{(R, N) \text{ or } (N, R)\} \xrightarrow{\gamma} (N, R) \xrightarrow{\beta} (N, N)$

Sequence III ($\alpha > \beta > \gamma$) : $(N, R) \xrightarrow{\alpha} \{(R, N) \text{ or } (N, R)\} \xrightarrow{\beta} (R, N) \xrightarrow{\gamma} (N, N)$

In each sequence, the labels below the arrows indicate the switchpoints for c_{2N} that trigger the change in equilibrium. Think of sequences I, II and III as corresponding to large, intermediate and small F_1/F_2 respectively (i.e., different *relative* R&D costs). Qualitatively, sequence I is identical to the analysis of the previous section, and the observations summed up in Proposition 2 above all apply (see Lemma 2(a) below for a proof that equilibrium social welfare jumps upwards at $c_{2N} = \beta$). The only difference is that firm 1 always chooses N , rather than R .

Fig. 4 plots equilibrium social welfare in sequence III, the only sequence where all three possible equilibria exist uniquely.²⁸

[FIG. 4 HERE]

Lemma 2 shows that two features of Fig. 4, $W(N, N) > W(N, R)$ at $c_{2N} = \beta$ and $W(R, N) > W(N, N)$ at $c_{2N} = \gamma$, are general:

Lemma 2: Assume that $F_1 > F_{1R}^*$. (a) Assume also that $c_{2R} > c_{1N}$. $W(N, N) > W(N, R)$ whenever (N, N) is the unique subgame perfect equilibrium, which requires $F_1 > F_{1N}^*$ and $F_2 > F_{2N}^*$ or $c_{2N} \in (c_{2R}, \min\{\beta, \gamma\})$. (b) $W(R, N) > W(N, N)$ whenever (R, N) is a subgame perfect equilibrium, which requires $F_1 < F_{1N}^*$ and $F_2 > F_{2R}^*$ or $c_{2N} \in (\gamma, \alpha)$.

²⁷ If one imagines Fig. 2 as dividing (F_1, F_2) -space into 9 cells using the solid and dashed lines, then each sequence corresponds to a different path from the middle cell in the bottom row to the top right cell.

²⁸ As Lemmas 2 and 3 below show, equilibrium social welfare in sequence II is higher under (R, N) than under (N, R) when there are two equilibria, as in sequence III; and it jumps upwards when c_{2N} falls below β , as in sequence I.

Proof: (a) If $c_{2N} < \beta$, then firm 2 prefers (N, N) to (N, R) , so a sufficient condition for $W(N, N) > W(N, R)$ is $\pi(c_{1N}, c_{2N}) + S(c_{1N} + c_{2N}) > \pi(c_{1N}, c_{2R}) + S(c_{1N} + c_{2R})$. This condition ensures that the rest of society (i.e., firm 1 plus consumers) prefers (N, N) . If $c_{2R} > c_{1N}$, then the sufficient condition holds for all $c_{2N} > c_{2R}$: LHS = RHS at $c_{2N} = c_{2R}$, and $\partial\text{LHS}/\partial c_{2N} > 0$ for all $c_{2N} > c_{1N}$. (b) If $c_{2N} > \gamma$, then firm 1 prefers (R, N) to (N, N) , so a sufficient condition for $W(R, N) > W(N, N)$ is $\pi(c_{2N}, c_{1R}) + S(c_{1R} + c_{2N}) > \pi(c_{2N}, c_{1N}) + S(c_{1N} + c_{2N})$. This condition ensures that the rest of society (i.e., firm 2 plus consumers) prefers (R, N) . Given that $c_{1N} \in (c_{1R}, c_{2N}]$, the sufficient condition holds: LHS = RHS at $c_{1N} = c_{1R}$, and $\partial\text{RHS}/\partial c_{1N} < 0$ for all $c_{1N} < c_{2N}$.

In particular, Lemma 2(a) shows that the transition from (N, R) to (N, N) in sequences I and II, which occurs in those two sequences at $c_{2N} = \beta$, is associated with an upwards jump in social welfare.²⁹ This might seem paradoxical because the sum of unit costs rises when firm 2 abandons its R&D plans. At $c_{2N} = \beta$, the welfare change is the effect on firm 1 plus consumers of an increase in firm 2's unit cost from c_{2R} to c_{2N} (because firm 2 is itself indifferent between (N, R) and (N, N) at $c_{2N} = \beta$). The jump in welfare arises because of strategic substitution on the product market: firm 1 expands at the expense of 2 when 2's unit cost rises, which cuts production costs on the redistributed output. The same mechanism of strategic substitution, although working to lower welfare, contributes to the result in Lemma 2(b). In sequence III, the transition from (R, N) to (N, N) at $c_{2N} = \gamma$ is associated with a jump downwards in social welfare as firm 1 abandons its R&D plans. The rise in firm 1's unit cost from c_{1R} to c_{1N} harms the rest of society. Strategic substitution on the product market implies that firm 2 grows at the expense of firm 1 when 1 switches from R to N , which is an inefficient redistribution of production.

In all three welfare comparisons in Lemmas 1 and 2, only one firm alters its R&D choice between the outcomes compared. Consequently, both Lemmas use the same method of proof. On the interval where the R&D-choice-changing firm has a given best response (either R or N), we define a sufficient condition for ranking social welfare in the two

²⁹ The condition $c_{2R} > c_{1N}$ in Lemma 2(a) is tighter than $c_{2N} > c_{1N}$, and it rules out leap-frogging by firm 2 (whether or not firm 1 undertakes R&D). Laggards must first catch up with leaders before overtaking them. This seems a sensible assumption given the very large within-industry variation in TFP across firms that is typically observed in the data (Haskel and Martin, 2002). It implies that 1's R&D activity is *innovative*, having the effect of moving the industry's technology frontier outwards, whereas 2's is purely *imitative*, concerned only with catch-up. (2's R&D activity would combine both types if $c_{1N} > c_{2R}$.)

outcomes, which is based on the preference of the rest of society (i.e., consumers plus the firm with an unchanged R&D decision). Moreover, in both Lemmas, we isolate conditions under which the outcome that *maximises firm 1's R&D spending lead over firm 2 is welfare-superior*.

Lemma 3 differs from the previous two because both firms' R&D choices change across the outcomes compared, (R, N) and (N, R) . Therefore, the method of proof also differs. In moving between the equilibria (R, N) and (N, R) , we certainly know that the firm that takes up (abandons) R&D gains (loses). The effect on consumers is unclear, depending on whether $c_{1R} + c_{2N} \geq c_{1N} + c_{2R}$, which determines the price change. Lemma 3 aggregates these effects:³⁰

Lemma 3: Assume that $F_1 > F_{1R}^*$ and $c_{2R} > c_{1N} + (c_{1N} - c_{1R})/3$. $W(R, N) > W(N, R)$ whenever (R, N) is a subgame perfect equilibrium, which requires $F_1 < F_{1N}^*$ and $F_2 > F_{2R}^*$ or $c_{2N} \in (\gamma, \alpha)$.

Proof: $c_{2N} > \gamma$ is equivalent to $F_1 < F_{1N}^*$, and $c_{2N} < \alpha$ is equivalent to $F_2 > F_{2R}^*$. $W(R, N) > W(N, R)$ can be expanded to give an inequality of the form $\{\dots\} > F_1 - F_2$. We can thus construct a sufficient condition for $W(R, N) > W(N, R)$ on $c_{2N} \in (\gamma, \alpha)$ by setting $F_1 = F_{1N}^*$ (i.e. as large as possible) and $F_2 = F_{2R}^*$ (i.e. as small as possible). This gives $\pi(c_{1N}, c_{2N}) + S(c_{1R} + c_{2N}) > \pi(c_{1N}, c_{2R}) + \pi(c_{2R}, c_{1N}) - \pi(c_{2R}, c_{1R}) + S(c_{1N} + c_{2R})$. The RHS is independent of c_{2N} , and $\partial\text{LHS}/\partial c_{2N} > 0$ for all $c_{2N} > c_{2R}$ iff $c_{2R} > c_{1N} + (c_{1N} - c_{1R})/3$. At $c_{2N} = c_{2R}$, the sufficient condition holds iff $\pi(c_{2R}, c_{1R}) + S(c_{1R} + c_{2R}) > \pi(c_{2R}, c_{1N}) + S(c_{1N} + c_{2R})$. In turn, this condition holds for all $c_{1N} \in (c_{1R}, c_{2R}]$: LHS = RHS at $c_{1N} = c_{1R}$, and $\partial\text{RHS}/\partial c_{1N} < 0$ for all $c_{1N} < c_{2R}$.

Taken together, Lemmas 1, 2(b) and 3 imply that *whenever* (R, N) arises in equilibrium, it is associated with higher social welfare than the other three outcomes.³¹

Strategic substitution plays a role in Lemma 3. To highlight it, consider the special case

³⁰ The condition $c_{2R} > c_{1N} + (c_{1N} - c_{1R})/3$ is more demanding than our “no leap-frogging” condition $c_{2R} > c_{1N}$ in Lemma 2(a). The two converge as the size of 1's process innovation tends towards 0.

³¹ This finding is reminiscent of Result 2 in Mills and Smith (1996), who show in a completely symmetric game of R&D competition in Cournot duopoly (i.e., $c_{1N} = c_{2N} > c_{1R} = c_{2R}$ and $F_1 = F_2$ in our model) that if an asymmetric “chicken” equilibrium exists (i.e., only one firm does R&D), it is the welfare-optimal outcome. Of course, as in our analysis, this is only “second best” welfare optimality because Cournot competition on the product market is taken for granted. (However, for criticism of the robustness of the duopoly assumption in Mills/Smith, see Elberfeld, 2003.)

where $F_1 = F_2$ and the innovation *size* is common across firms ($\Rightarrow c_{1R} + c_{2N} = c_{1N} + c_{2R}$). Together, these assumptions mean that the welfare comparison of (R, N) and (N, R) depends only on industry variable profits in the two cases. The common innovation size assumption means that industry output and price (and, therefore, consumer surplus and revenue) are the same in both cases. Therefore, $W(R, N) > W(N, R)$ if and only if $\pi(c_{1R}, c_{2N}) + \pi(c_{2N}, c_{1R}) > \pi(c_{1N}, c_{2R}) + \pi(c_{2R}, c_{1N})$. Given our assumed ranking of unit costs ($c_{2N} > c_{2R} > c_{1N} > c_{1R}$), strategic substitution means that this condition holds because the spread of marginal costs is greater in (R, N) (Salant and Shaffer, 1999).³²

Taking the results of the previous section and this one together, there are five distinct transitions between equilibria that can be caused by reducing firm 2's initial unit cost. With "small" F_1 , the transition is from (R, R) to (R, N) . With "large" F_1 , the transition in sequence I is from (N, R) to (N, N) ; sequence II adds the potential transitions (N, R) to (R, N) to (N, R) ;³³ finally, sequence III adds (R, N) to (N, N) . Proposition 3 sums up the preceding analysis and summarises the normative effects of these transitions between equilibria:

Proposition 3: Assume an asymmetric, linear Cournot duopoly where (discrete and nondrastic) process R&D decisions are endogenous. (a) Whenever the major firm chooses to invest in R&D in equilibrium but the minor firm does not, social welfare is maximised. (b) Catch-up by the minor firm increases (decreases) social welfare discretely if it increases (decreases) the major firm's R&D spending lead over the minor firm.

To recap briefly on terminology, the major (large) firm is 1, and the minor (small) one is 2. Firm i 's spending on R&D belongs to $\{0, F_i\}$, depending on whether i undertakes R&D. Firm 1's *R&D spending lead* is its spending on R&D minus firm 2's.

In addition to the discrete changes in social welfare that occur when catch-up by firm 2 changes equilibrium R&D choices, there are also continuous changes in social welfare

³² The common innovation size assumption ($c_{iN} - c_{iR} = \delta > 0$ for $i = 1, 2$) means that industry revenue is the same in (R, N) and (N, R) . Therefore, given $F_1 = F_2$, $W(R, N) > W(N, R)$ if and only if industry production costs are lower in (R, N) . This requires $c_{1R}q_1^R + (c_{2R} + \delta)(\bar{Q} - q_1^R) < (c_{1R} + \delta)q_1^N + c_{2R}(\bar{Q} - q_1^N)$, where q_1^R and q_1^N are 1's equilibrium outputs in (R, N) and (N, R) respectively, and \bar{Q} is the common level of industry output. Simplifying, the inequality becomes $q_1^R + q_1^N > \bar{Q}$, which holds because $c_{1N} < c_{2R}$ implies that $q_1^R > q_1^N > \bar{Q}/2$.

³³ If (N, R) is selected in the central "chicken" area of Fig. 2, then these two transitions do not arise in sequence II.

when equilibrium R&D choices remain unchanged. Social welfare in (N, R) is independent of c_{2N} because 2's unit cost is c_{2R} . Social welfare in both (R, N) and (N, N) is U-shaped in c_{2N} for the reasons behind Proposition 1. As in the previous section, the curvature of a given $W(\cdot, \cdot)$ function is independent of the R&D fixed costs F_1, F_2 , but the unit-cost switchpoints between different R&D regimes in equilibrium do vary with the fixed costs of R&D. Thus, by setting F_2 sufficiently small, we ensure that firm 2 chooses R whenever social welfare would otherwise be increasing in c_{2N} . (Recall that reducing F_2 pushes both α and β downwards.)

Proposition 3(b) generalizes Proposition 2(a) to show that *any* slight narrowing of the initial unit-cost gap between the firms, $c_{2N} - c_{1N}$, that leads to a widening of the equilibrium unit-cost gap, by causing firm 1's R&D spending lead over firm 2 to rise, raises social welfare discretely. We have also uncovered an additional mechanism through which catch-up by firm 2 can increase 1's R&D spending lead and social welfare. In the last section, firm 1 always undertook R&D, and the mechanism was that catch-up by firm 2 caused it to abandon R&D. In this section, we have shown that catch-up by firm 2 can cause *both* firms to change their R&D decisions. For example, assume in sequence III that whenever (R, N) and (N, R) both exist as equilibria, (N, R) is played. Then, when c_{2N} is pushed below β , the equilibrium changes from (N, R) to (R, N) , which produces a larger jump in social welfare than the transition from (N, R) to (N, N) . Pushing c_{2N} below β makes N a dominant strategy for firm 2 and, in response, firm 1 invests in R&D.

6 Conclusion

We have analysed the welfare effects of catch-up by a minor firm in an asymmetric Cournot duopoly. The catch-up takes the form of a narrowing of the initial unit-cost gap between the firms. In the short run, where the firms' process technologies are fixed, catch-up by the minor firm produces the Lahiri/Ono (1988) result. If the initial unit-cost gap is sufficiently large, then reducing the minor firm's unit cost causes social welfare to fall because it causes a socially inefficient reallocation (i.e., major-to-minor) of initial production.

In the long run, the firms' process R&D investments are endogenously determined to maximize profits. If catch-up by the minor firm causes the major firm's R&D spending lead over its rival to grow (through changes in R&D investment decisions), then social welfare jumps upwards. By extending the major firm's R&D spending lead, the reduction in the

initial unit-cost gap between the firms raises social welfare discretely because it widens the equilibrium unit-cost gap. This widening provokes a socially efficient reallocation (i.e., minor-to-major) of initial production level.

We have interpreted our model as one of R&D or technology choice, following Mills and Smith (1996). However, other interpretations are possible. For example, a qualitatively identical game would be played if two firms from different home countries choose between exporting and greenfield-FDI as alternative means of serving a product market in a “third” country. Under this interpretation, our strategies R and N become greenfield-FDI and exporting respectively, and catch-up by firm 2 becomes a fall in the bilateral trade cost between 2’s home country and the third/host country.

Finally, although our quantitative results are derived using a rather stylized model, we believe that our qualitative insights will survive in more general contexts – e.g., for a broad class of cost/demand functions, and under Bertrand competition on the product market. The key mechanism behind our results is that catch-up by the minor firm causes it to steal business from the major firm in product-market equilibrium, and this is a standard characteristic of oligopoly models. Given this expectation, our findings are most clearly illustrated using a simple model.

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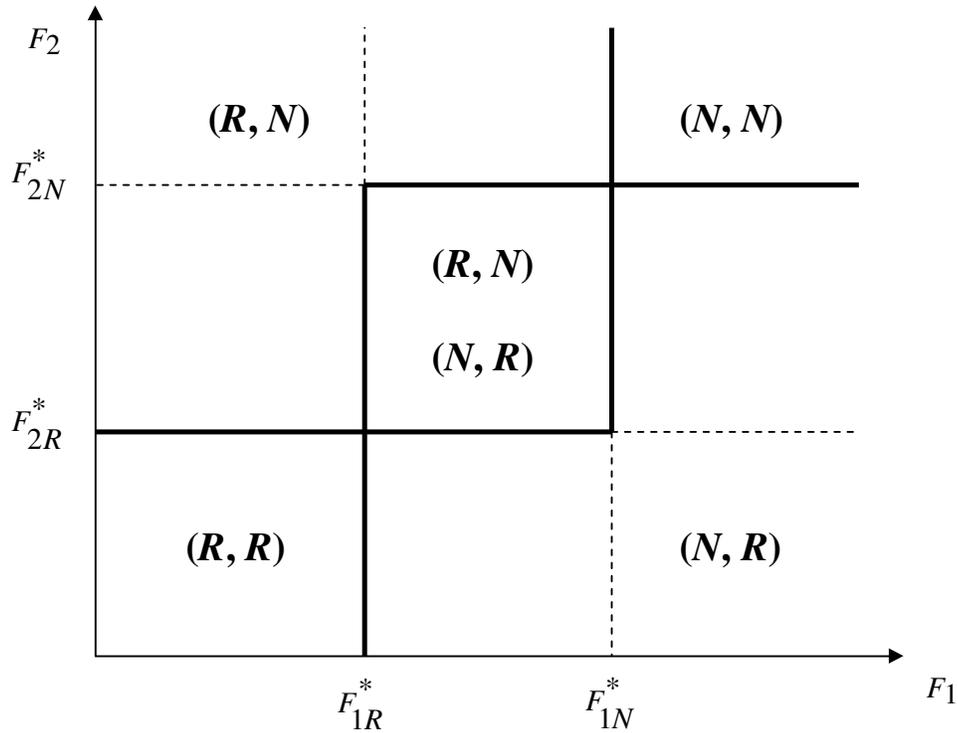
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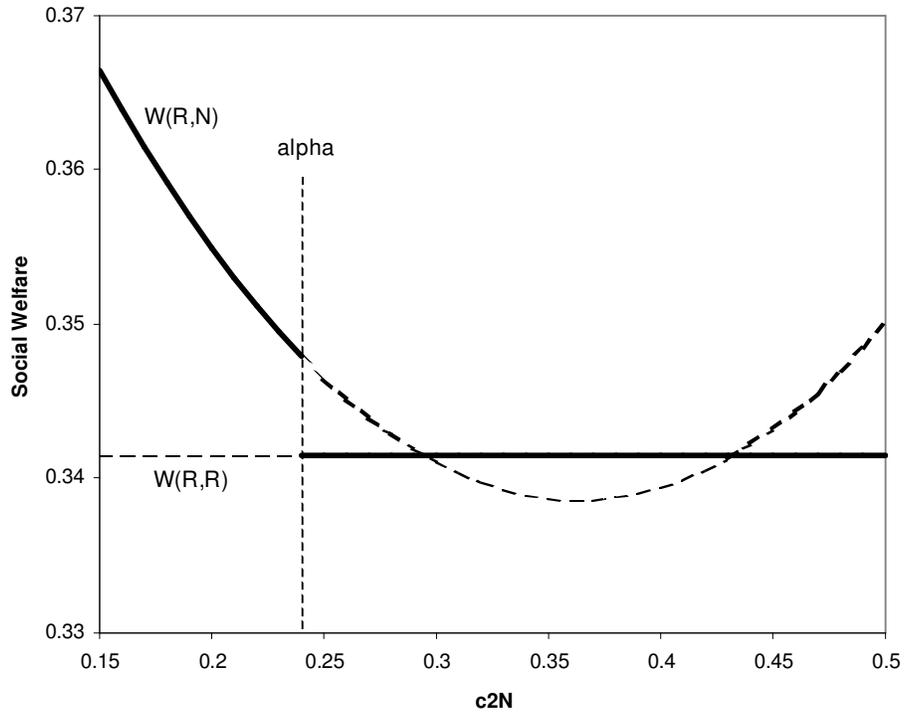
		Firm 2	
		<i>N</i>	<i>R</i>
Firm 1	<i>N</i>	$\pi(c_{2N}, c_{1N})$	$\pi(c_{2R}, c_{1N}) - F_2$
	<i>R</i>	$\pi(c_{2N}, c_{1R})$	$\pi(c_{2R}, c_{1R}) - F_2$
		$\pi(c_{1N}, c_{2N})$	$\pi(c_{1N}, c_{2R})$
		$\pi(c_{1R}, c_{2N}) - F_1$	$\pi(c_{1R}, c_{2R}) - F_1$

(Above) **Figure 1: Payoff Matrix**



(Above) **Figure 2: Subgame Perfect Equilibria**

Notes: F_{1R}^* is independent of c_{2N} . $F_1 \leq F_{1N}^*$ is equivalent to $c_{2N} \geq \gamma$. $F_2 \leq F_{2R}^*$ ($F_2 \leq F_{2N}^*$) is equivalent to $c_{2N} \geq \alpha$ ($c_{2N} \geq \beta$).



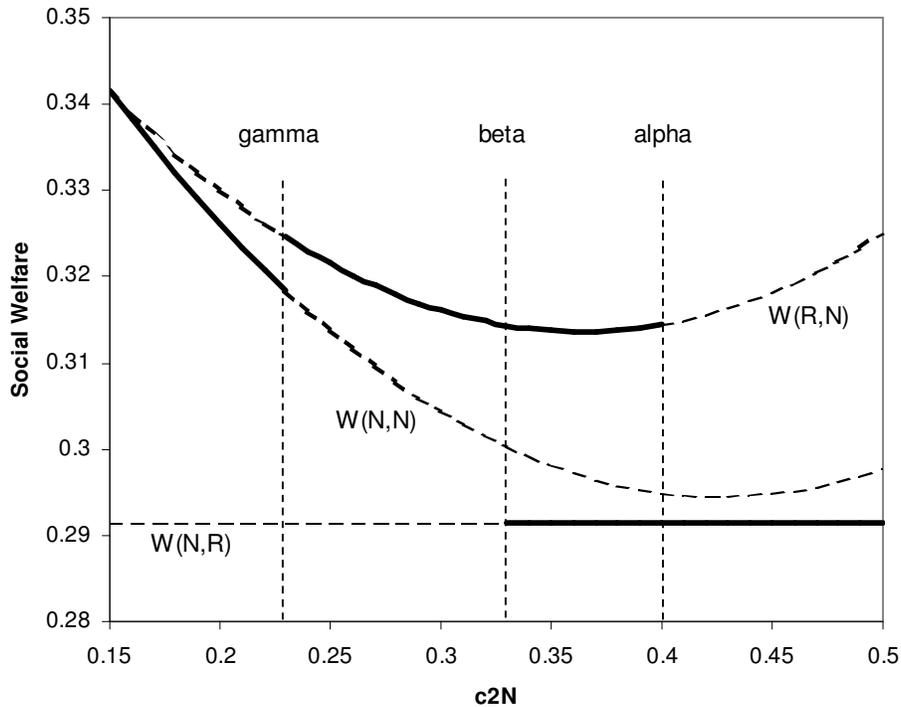
(Above) **Figure 3: Equilibrium Social Welfare if Major Firm's R&D is Cheap ($F_1 \leq F_{1R}^*$)**

Notes:

Equilibrium social welfare is the **solid bold** line.

$c_{2N} \geq \alpha$ is equivalent to $F_2 \leq F_{2R}^*$.

Parameter values: $c_{1N} = 0.1$, $c_{1R} = 0$, $c_{2R} = 0.15$, $F_1 = F_2 = 0.025$; so $\alpha \cong 0.24$.



(Above) **Figure 4: Equilibrium Social Welfare if Major Firm's R&D is Costly ($F_1 \geq F_{1R}^*$)**

Notes:

Equilibrium social welfare is the **solid bold** line.

$c_{2N} \geq \gamma$ is equivalent to $F_1 \leq F_{1N}^*$. $c_{2N} \geq \alpha$ ($c_{2N} \geq \beta$) is equivalent to $F_2 \leq F_{2R}^*$ ($F_2 \leq F_{2N}^*$).

Parameter values: $c_{1N} = 0.1$, $c_{1R} = 0$, $c_{2R} = 0.15$, $F_1 = F_2 = 0.05$; so $\alpha = 0.4$, $\beta \cong 0.33$, $\gamma \cong 0.23$.

Appendix Figure: Critical F -values and the Determination of α , β and γ

This figure illustrates sequence I from section 5 ($\gamma > \alpha > \beta$). From it, we see that $c_{2N} \geq \gamma$ is equivalent to $F_1 \leq F_{1N}^*$; and $c_{2N} \geq \alpha$ ($c_{2N} \geq \beta$) is equivalent to $F_2 \leq F_{2R}^*$ ($F_2 \leq F_{2N}^*$). Thus, using Figure 2, we can write down conditions on c_{2N} for a given subgame perfect equilibrium to exist.

