Economics
The Open-Access, Open-Assessment E-Journal

Discussion Paper
No. 2009-33 | July 10, 2009 | http://www.economics-ejournal.org/economics/discussionpapers/2009-33

Minimum Quality Standards and Novelty Requirements in a One-Shot Development Race

Jacek Prokop, Pierre Regibeau, and Katharine Rockett
Warsaw School of Economics; University of Essex and CEPR; University of Essex and CEPR

Please cite the corresponding journal article:
http://www.economics-ejournal.org/economics/journalarticles/2010-15

Abstract
The authors examine the timing and quality of product introduction in an R&D stopping game, where they allow for horizontal and vertical differentiation in the product market. They observe that discontinuous changes in introduction dates can occur as firms' abilities as researchers change. Further, the authors observe differences in the social optimality of entry patterns depending on the underlying research abilities of the firms. Minimum quality standards and novelty requirements can play a role in correcting these suboptimal patterns of entry. The authors find that increasing the novelty requirement does not necessarily increase either the profits or, consequently, the investment levels of the initial innovator, contrary to much of the cumulative innovation literature. When the research abilities of the firms differ, either the high ability firm or the low ability firm may be the first mover. Policy interventions have much more ambiguous welfare effects in this asymmetric case, as they can change the order of entry.

Paper submitted to the special issue
The Knowledge-Based Society: Transition, Geography, and Competition Policy

JEL: L15, L16, O31, O33, O34

Keywords: Innovation; minimum quality standards; novelty requirements; stopping game

Correspondence
Katharine Rockett, Department of Economics, University of Essex, Wivenhoe Park, Colchester CO4 3SQ, England; e-mail address: kerock@essex.ac.uk

The authors would like to thank Steve Garber, Kai-Uwe Kuhn and Carmen Matutes for helpful comments. Pierre Regibeau and Katherine Rockett acknowledge support of the Spanish DGICYT under grant number PB-92-1138, and Katherine Rockett acknowledges sponsorship by the Research Council of Norway (Project 172603/V10).

© Author(s) 2009. Licensed under a Creative Commons License - Attribution-NonCommercial 2.0 Germany

1. Introduction

In a large number of industries, regulations on the conditions of entry, including product standards, have significant and long-lasting effects on industry behaviour and structure. Riordan (1992) analyses such effects in a theoretical model capturing features of cable TV and telephone technologies, while Gruber and Verboven (2001) find empirical evidence for long-lasting effects in mobile telecommunications. Boom (1995), Herguera and Lutz (1998) and Motta and Thisse (1993) examine the consequences of a variety of regulatory measures, such as product safety and environmental standards in an international context. This type of control of "product quality" is still topical, as shown by Manski (2009) recent an opinion piece advocating a change in FDA procedures to allow limited diffusion of new drug entities before they have been fully investigated according current "quality control" procedures.

Theoretical treatments initially suggested that minimum quality standards were socially very desirable. For example Ronnen (1991), in a seminal paper, shows that, in a Shaked and Sutton framework with endogenous (costly) quality, a minimum quality standard unambiguously raises consumer surplus, the low quality producer's profit, and industry surplus while only harming the high quality producer. By forcing the low quality seller to improve its product a binding minimum quality standard also leads the high-quality sellers to raise its own quality in an effort to alleviate price competition[1]. While this analysis focuses on static efficiency effects, Riordan's (1992) work, analyses the dynamic effects of regulation on the timing of adoption of

[1] This result has been shown to be sensitive to the underlying assumptions on cost (Crampes and Hollander, 1995), preference (Kuhn, 2007) and the number of competitors in the market (Scarpa, 1998).

quality-improving technologies. Riordan's interest is in the dynamic consequences of price regulation and protection from entry. In his model, regulation is used to correct social inefficiencies in the timing of entry.

Our paper is very much in the spirit of Riordan (1992) since we also consider a framework where firms strategically choose their timing of entry. However, we examine the effect and optimal uses of two different policy tools, namely minimum quality standards and novelty requirements. Novelty requirements, seen as a minimum "quality increment" required of follow-up products, have already been analysed in papers such as Scotchmer and Green(1990), and Matutes, Régibeau and Rockett (1996) for a two-stage sequence of innovations, and O'Donoghue (1998) and Hopenhayn and Mitchell (2001, 2006) in quality ladder models.

More precisely, we model a one-shot research and development stopping game between two firms where the payoffs depend on the difference in the qualities of the introduced products. Firms may improve their products during a waiting period before entry. The longer they wait, the higher the quality of their product. Once the entry decision is taken, the product design is frozen. Introduction can occur only once. The profits of the entrants depend on both the quality level of the final product and on the difference in product qualities when both firms are active in the market. In contrast to earlier uses of this sort of timing model, such as Dutta, Lach and Rustichini (1990) or Régibeau and Rockett (1996 and 2005), we allow firms to have different levels of "skill" in innovation. Indeed the derivation of equilibria for such an asymmetric "stopping game" is itself of some independent interest.

Dutta, Lach and Rustichini (1990) show that, with symmetric firms two types of equilibria can arise within this type of stopping game. Both equilibria are characterised by staggered introduction, where one firm leads with a low quality product on which it earns temporary monopoly rents, while the other enters later with a higher quality product. In the first type of equilibrium, the second mover earns higher lifetime profit than the first mover and, given the expected interval between the two product entries, the first mover maximises its total discounted profits. There is no rent dissipation since the two firms do not compete to be first to market. We refer to this case as a "stand-alone" equilibrium. There are also pre-emption equilibria, where there is rent dissipation and rent equalisation as firms "race" to move forward their entry date up to the point where they are indifferent between moving second or first.[2]

As we show, because small changes in our parameters can change the type of equilibrium that prevails, there can be abrupt changes in the equilibrium entry times and profitability of entering firms for small changes in their (identical) research ability. Indeed, while the firms "race"-- and so dissipate profits -- when they are both highly skilled, less-skilled firms tend to settle into an equilibrium profit without pre-emption.

When we allow firms to have asymmetric skill levels, we find no necessary correlation between skill and either quality of the final product introduced or the order of entry. This result, which is broadly similar to that of Riordan (1992), stands in contrast to Quint and Einav (2005) who adopt a war of attrition model to determine the order of entry. The crucial difference is that these two authors do not allow the

[2] This is the type of equilibria studied in the seminal paper by Fudenberg and Tirole (1985).

quality (and hence the profitability) of an entrant to improve with waiting: while a cost is sunk each period before entry, no gain accrues in exchange for this cost. In our framework, the cost incurred during the waiting period results in an improved product that will eventually be offered on the market.

Our result that the "better" firm needs not enter first is also related to Argenziano and Dengler (2008) who study entry behaviour of firms that differ in production cost (or, equivalently, flow profits upon entry). They find that, for the same entry cost, the firm with the higher flow profits always enters first in a two-firm waiting game model like ours but that this result cannot be generalised to three firms. While the more efficient firm has a stronger incentive to enter than a less efficient firm, all else equal, the first mover must also take into account how long it will be before the rival enters. If a less efficient firm tends to follow more closely than a more efficient firm, then the more efficient firm may decline the leadership position. Indeed, in their three-firm case, a less efficient firm always moves first. In our case, the firms do not have exogenously assigned flow profit levels, but rather choose these levels endogenously by means of the timing game. Still, the basic intuition for our order of entry result is similar: while the more skilled firm has a stronger incentive to enter, all else equal, it must balance this against the fact that the less skilled firm may still enter in the future with a high quality product and this will reduce future profits. If the lower skilled firm tends to follow relatively quickly, then the high skilled firm may postpone entry, leaving the first mover position to the low-skilled firm.

The motivation for introducing policy instruments into our framework is that the privately optimal and the socially optimal timing of entry need not be the same in a stopping game such as ours, even when the skill levels of the two firms are the same. Riordan's (1992) work concentrates on a case where the private incentives to enter are much too great. Hence, he focuses on policy instruments such as entry control that can effectively retard entry. In our framework, the leader may enter too early or too late, and the follower may enter with either more or less than the socially optimal delay. The pattern of entry tends to be related to the size of the innovative step. When firms are highly skilled in research, so that quality increments come very cheaply, the leader tends to introduce socially too early, while the follower tends to introduce socially too late. By contrast, when research skill is very low, both the leader and the follower move socially too fast to market. For intermediate ranges, the follower tends to enter too quickly, while the leader may lag or lead the socially optimal introduction date. As a result, minimum quality standards, which effectively prevent entry into the market before a given date, may or may not improve welfare. When research skill is symmetric and either very high or quite low, there always exists a minimum quality standard that improves welfare. For intermediate ranges, this need not be the case.

When we allow for research abilities to differ, the pattern is even more complex. We observe first that a minimum quality standard can actually *change the order of entry*. As this can generate earlier participation by a high ability firm, this can improve welfare. Unfortunately, and contrary to the symmetric ability case, the minimum quality standard can also affect the delay between first and second product introductions. More precisely, when the more able firm moves first, a minimum quality standard can also constrain the date of entry of the second mover as the lower-skilled firm will only be able to satisfy the standard significantly later than the more able first-mover. As the difference in skill levels gets more pronounced, this effect becomes larger. Hence, the welfare effect of the minimum quality standard depends crucially on the spread of research abilities of the firms involved.

Since welfare is affected by both the date of first introduction and the delay that elapses between first and second entry, a novelty requirement is a natural instrument to introduce into this setting. By imposing a minimum quality difference between first and second mover, a novelty requirement effectively increases the time gap between the two dates of entry. Novelty requirements have been studied in quality ladder models in a series of papers, including Hopenhayn and Mitchell (2001). That paper takes a mechanism design approach, where the innovator's type determines the entry timing of the follower and is private information of the innovator. Our focus is different at several levels: we assume full information on type, and instead concentrate on deriving the timing of entry endogenously in a stopping time framework. Further, our modelling allows for discontinuous change in the type of entry equilibrium. Importantly, while our model includes quality improvements, it is not the case that the higher quality product must "stand on the shoulders" of the lower quality product. Our model of quality increase is not a model of cumulative innovation, where a follower firm's innovation requires the existence of the lead firm's innovation to be placed on the market. Instead, the research paths of the two firms can be developed independently of each other.

We limit our analysis to the case of firms with identical research abilities. We find that, like a minimum quality standard, the novelty requirement improves welfare for high or low research abilities, with no necessary improvement over an intermediate range. We get some rather counter-intuitive results. For example, when the equilibrium is pre-emptive, a binding novelty requirement *decreases the profits of both firms*, so that stronger patent protection is associated with lower profits for all firms in the industry. The intuition for this result is very different from the recent literature on the negative effects of strong patent protection. In our case, the novelty requirement lowers the follower's profit, and so reduces the "opportunity cost" of moving early for the leader. As a result, the leader enters too fast with a very low quality product as part of pre-emptive behaviour. In other words, by worsening the prospects of the second mover, a stronger novelty requirement intensifies the race for the first innovation, dissipating rents. Welfare can also move quite discontinuously as a function of the novelty requirement. For example, as we pass from the range of abilities for which pre-emptive behaviour occurs to that where stand alone behaviour prevails, we observe a discontinuous jump in the welfare benefit of the novelty requirement.

The rest of the paper is organised as follows. Section 2 presents the model and some preliminary results on the types of equilibria we observe in our model. Further, we show that the non-cooperative choice of introduction dates does not generally maximise welfare in our model. We move on quickly from these, as our main interest is not in the baseline equilibria but the effect of two policy instruments, minimum quality standards and novelty requirements, on these equilibria. We consider the effect of the policy instruments in Section 3. Section 4 considers how these results change when asymmetries in skills are introduced to the model. Section 5 concludes the paper.

2. The Model

Two firms (indexed by $i = A, B$) invest in research and development (R&D) to introduce their own version of a new product. The quality of the products is the result of a game of timing. Starting at time 0, each firm can conduct research to improve the quality of the product that it will introduce, q_i, at rate θ_i per unit of time. Hence the quality obtained by firm j at time t is $q_i(t) = \theta_i t$, where θ_j measures firm j's "skill" in research. Given their respective values of θ (which are common knowledge) each firm must decide when to introduce its version of the new product. We make the simplifying assumption that each firm can introduce its product only once and that the quality of its product is fixed from the date of introduction on. This allows us to focus our attention on the timing of introduction without dealing with the issue of "persistence of monopoly"[3]. However, this assumption is also justified in concrete situations where further improvements are difficult once the basic features of the product have been "locked in". For example, the single introduction assumption seems reasonable for the case of many drugs, such as anti-cholesterol drugs. As explained Deibold (1990), the profitability of these drugs mostly depends on the quality of basic product first introduced by each firm, the following improvements having been of -- relatively -- minor importance.

The demand for the new products is represented by a model with both a vertical and a horizontal dimension. Consumers are uniformly distributed with unit density on a line segment of length 1. The products offered by the two firms are located at the opposite ends of the line. This horizontal differentiation reflects Rosenberg's (1982)

[3] Dutta, Lach and Rustichini (1990) examine "incumbency inertia" as a focus of their work. Although one would be tempted to assume that an incumbent would enter late in a stopping game framework for fear of cannibalising its sales from an old technology, they show that the incumbent may very well enter earlier because the entrant has superior ability to commit *not to* enter early.

finding that different innovations within the same area tend to focus the needs of different user groups. Each consumer purchases at most one unit of the good to maximize the following utility function:

$$U = max(q\text{-}p\text{-}cx,\ 0)$$

Where q is the quality of the product purchased, p is the price paid and x is the "distance" between the consumer's ideal specification of the good and the version of the good purchased. The variable c is the unit utility loss associated with such a discrepancy.

In each period, the profits of the firms depend on the quality of the products offered and on the number of producers who have entered the market. If firm i is the only firm marketing a product, then its monopoly profits are given by:

$$\pi_i^M(t_i) = \frac{q_i^2}{4c} \text{ if } 0 \le q_i \le 2c$$

$$q_i - c \text{ if } q_i > 2c$$

depending on whether the market is partially or completely served. When both firms offer a product in the market, firm i's profits are:

$$\pi_i^D(t_i, t_j) = \frac{c}{2}[1 + \frac{1}{3c}(q_i - q_j)]^2 \text{ if } -3c \le q_i - q_j \le 3c$$

$$q_i - q_j - c \qquad \text{if } 3c < q_i - q_j$$

$0 \qquad \text{if } q_j - q_i > 3c$

The first line corresponds to the case where both firms have positive market shares. The second and third lines reflect situations where the quality differential is so large that one of the two firms monopolises the market. Notice that, to keep the number of sub-cases to be considered down and unless otherwise stated we only deal with situations where the market is fully covered once both firms have introduced.

2.1 Equilibrium

In this section, we derive the basic equilibria of the model. An interesting feature that will emerge is that industries characterised by lower research "ability", in other words a lower rate of quality progress per unit time compared to the discount rate, will tend to be characterised by a larger difference in equilibrium profits between leaders and followers. As we explain below, this stems from a change in the type of equilibrium that occurs in low and high ability industries.

Each firm must choose an introduction date, given the introduction date of its rival. In other words, each firm must choose a date to stop increasing quality and fix the design of its product. In solving for the equilibrium we assume that the firms cannot commit *ex ante* to their date of introduction. In other words, we solve for the sub-game perfect equilibria of a game where – at each point in time – each firm who has not yet introduced its product must decide whether to introduce now or to proceed with further development. Formal proofs are included in the technical appendix.

We consider first the situation where both firms are of equal "research" ability, so that they each have the same value of θ. We first need to characterise the behaviour of the follower and then use this to derive the leader's behaviour. While the expression for the follower's optimal entry date carries some interest of its own, the salient characteristic for the public policies we will analyse below is that the lag between the leader's entry date and the follower's entry date is independent of the leader's date of entry when the firms' research abilities are symmetric. This is stated formally below for reference later:

Lemma 1: Defining the optimal entry date of the follower as t_i and the entry time of the leader as t_j, the optimal entry time of the follower is given as:

$t_i(t_j) = t_j + (1/r) + c/\theta.$ *for* $\theta/r > 2.55c$

$t_i(t_j) = t_j + (2/r) - 3c/\theta$ *for* $1.5c < \theta/r < 2.55c$

where r is the discount rate. Hence the delay between first and second entry, $t_i - t_j$ is independent of t_j.

Proof: See Appendix

The ratio θ/r is a measure of the amount of research progress the firm can expect per period compared to the rate of discount applied to that period. The lower parameter restriction, $1.5c < \theta/r$ ensures that the second mover is willing to wait once the first product is introduced. Since this is also the range over which a monopolist would find it optimal to enter with positive quality, we will assume that θ/r is greater than $1.5c$ for the rest of the paper. The limit that separates the two cases ($\theta/r = 2.55c$), is a point of discontinuity at which the elapsed time between first and second entry changes discretely. This discontinuity is the result of a change from a regime where the firms share the market after entry of the second firm to one where the follower appropriates the entire market and becomes a monopolist. We refer to these two cases below as "incremental" and "drastic" product innovations. When the innovation becomes drastic, the single firm left in the market can act as an unconstrained monopolist. In the incremental case, the firms remain constrained by each others' pricing behaviour.

It can be shown[4] that two types of equilibria exist in this "stopping" game. The situations giving rise to these equilibria are shown in figures 1.a and 1.b.. In these graphs, the discounted profits of the follower decrease as the leader introduces later. This is because the follower can only start to build up an advantage over the leader once the leader has introduced, so that a later date of first introduction simply pushes back the time at which the follower can start reaping profits. On the other hand, *given the optimal introduction delay of the follower*, the profit function of the leader has a unique maximum at t_S.

When research ability, θ, is relatively high compared to time preference, r, the leader finds it profitable to wait fairly long before fixing its design since the quality of the resulting product increases quickly at a low cost in terms of discounting. However, such waiting also pushes back the date at which the follower would be able to earn a profit to such an extent that the follower would in fact prefer to move first. There is therefore a "race to be first" which leads to an equilibrium where the profits of first and second movers are equalised at t_p. This is the situation depicted in figure 1.a..

[4] See our working paper for a formal derivation of the equilibria. Also, see Dutta, Lach and Rustichini (1990) for discussion of these types of equilibria in a general stopping game.

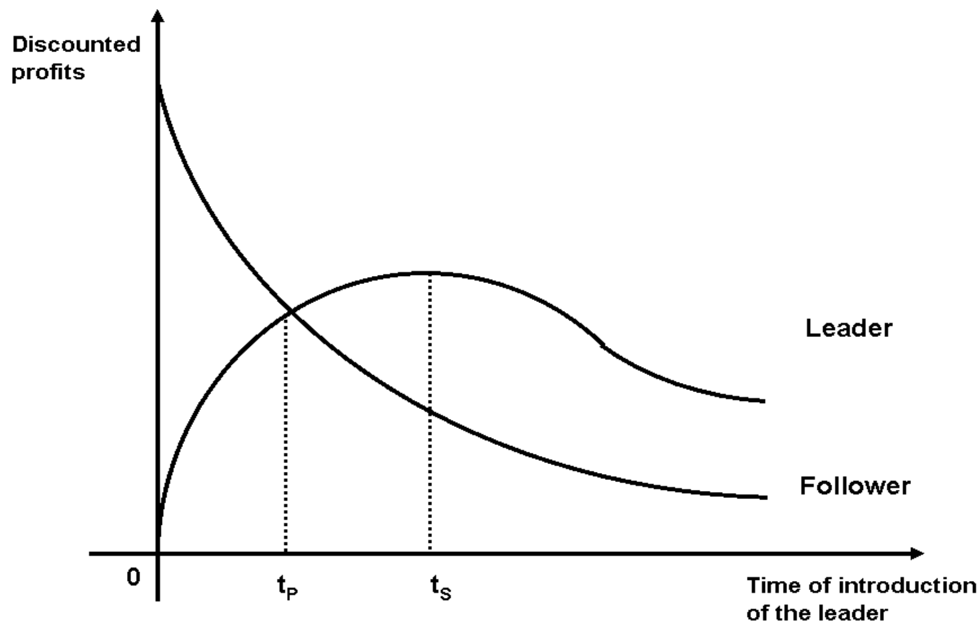

Figure 1.a.

Following Dutta et al. (1990), we call this a “pre-emption” equilibrium.

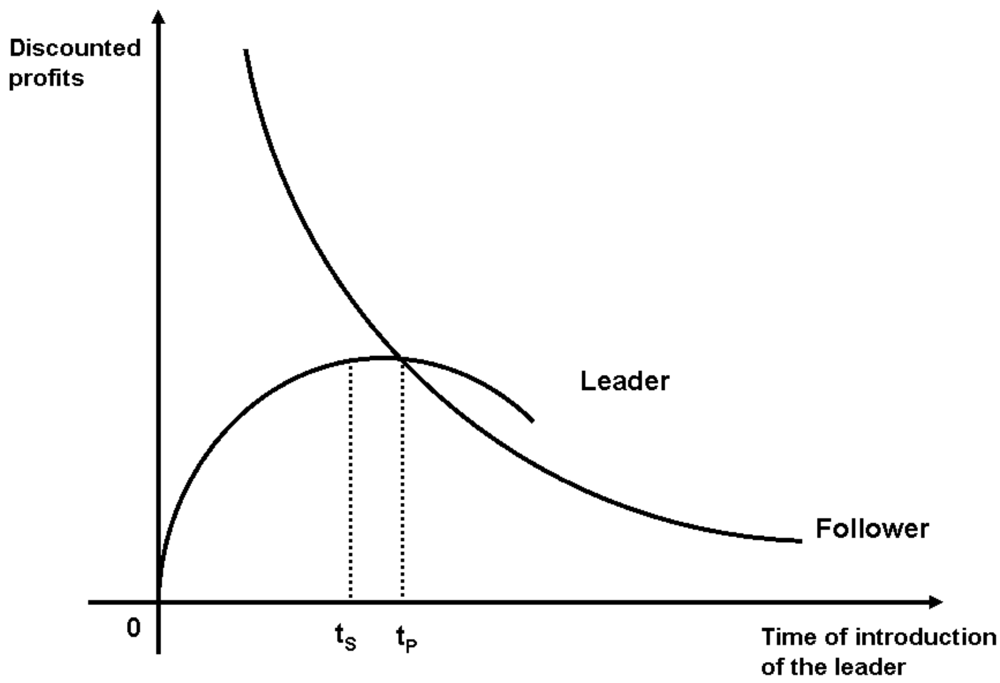

Figure 1.b.

For lower values of research ability compared to time preference, on the other hand, the leader may choose to move quickly enough that the follower is happy to move second. This shown in figure 1.b., where the two curves intersect to the right of the maximand t_s. Hence, in equilibrium, one firm moves at t_s and the other follows after the optimal delay specified in lemma 1. We call this type of equilibrium a "stand alone equilibrium"[5] . In such an equilibrium, the follower makes higher profits than the leader. Hence, we obtain the following characterisation of the equilibria of this game:

Proposition 1: If the research abilities of the two firms are limited, (i.e. $1.5c \leq \frac{\theta}{r} < 1.8c$), then there are two stand-alone subgame perfect equilibria in pure strategies where one firm introduces at time $t_{j\max} = \frac{1}{r} + \frac{c}{\theta} - \frac{2c}{\theta}\frac{Y}{1-Y}[1 - \frac{\theta}{3rc}]$ and the other firm introduces after the additional period defined in Lemma 1. For higher research abilities ($\frac{\theta}{r} \geq 1.8c$) there are two pre-emptive subgame perfect equilibrium outcomes, where one firm moves first at $t_p = \frac{c}{\theta} - \frac{2c}{\theta}\frac{Y}{1-Y}[1 - \frac{2\theta}{3rc}]$ and the other firm introduces after the additional period defined in Lemma 1.

Proof: See Appendix

2.2 Welfare

It is straightforward to determine the level of social surplus generated at each date. When firm A is a monopolist, introducing at time t_A, we have:

---

[5] Dutta, Lach and Rustichini call it a "maturation equilibrium".

$$SS^M = \frac{3q_A^2}{8c} \quad \text{if } q_A \le 2c$$

$$q_A - \frac{c}{2} \text{ if } q_A > 2c$$

and the entire market is served if and only if $q_A \ge 2c$. We will focus on this case, below.

Arbitrarily assuming that firm A introduces first in the duopolistic equilibrium, we have:

$$SS^D = q_B + \frac{q_A - q_B}{w} - \frac{c}{4} + 5[\frac{(q_A - q_B)^2}{36c}] \text{ if } q_B - q_A \le 3c$$

$$q_B - \frac{c}{2} \qquad\qquad \text{if } q_B - q_A > 3c$$

where both firms have positive market shares if $q_B - q_A \le 3c$ and firm A is a limit pricing monopolist if $q_B - q_A > 3c$.

Total discounted social surplus is given by:

$$\int_{t_A}^{t_B} SS^M e^{-rt} dt + \int_{t_B}^{\infty} SS^D e^{-rt} dt = \frac{1}{r}[SS^M (e^{-rt_A} - e^{-rt_B}) + SS^D e^{-rt_A}].$$

Let (t_A^s, t_B^s) be the social surplus maximising stopping dates for A and B, respectively.

The firms' non-cooperative choice of introduction dates will not generally maximise welfare. Indeed, the inefficiency may come at the level of either the first or second mover. Given the date of introduction of the first product, whether the follower moves too quickly or too slowly depends on the research "ability" of the industry. Specifically, if the ability is high enough that the follower enters with a drastic innovation then the follower tends to introduce too late compared to the socially optimal date. On the other hand, if ability is low enough that the follower only enters with an incremental innovation, then the follower will tend to introduce socially too quickly. This is stated formally in proposition 2.

Proposition 2: Assume that $\theta_A = \theta_B = \theta$. Given an initial date of introduction, t_A, the interval before the second product is introduced can be either socially too short (for $\frac{\theta}{r} < 2.55c$) or socially too long (for $\frac{\theta}{r} \geq 2.55c$).

Proof: see Appendix

The claims in proposition 2 are due to two opposing effects. On the one hand, waiting increases the quality of firm *B*'s product. While this raises both social surplus and firm B's profits from time t_B on, the increase in *B*'s profits is smaller than[6] the increase in social surplus as long as firm *B*'s rate of improvement is small enough that both firms remain in the market following *B*'s entry. This is because competition from the lower quality level places a limit on the surplus that *B* can extract from consumers and so allows some consumer surplus to remain with purchasers. Hence, firm *B*'s waiting time tends to be too small compared to the social optimum (t_B

[6] For $\frac{\theta}{r} \geq 2.55c$, it is equal to the increase in social surplus.

smaller than t_B^s) because the reward to its research falls short of the full social benefit it generates. On the other hand, waiting also postpones the introduction of *B*'s product. This cost of waiting for firm *B* is smaller than or equal to the cost of waiting for society because, as before, firm *B* cannot usually appropriate the full social benefit of an increase in the quality of its product[7]. This effect tends to make firm *B*'s waiting time too large compared to the social optimum (t_B greater than t_B^s). When research ability is high enough compared to time preference, firm *B* serves the whole market as a monopolist as soon as its good is introduced[8]. In this case, firm *B* can capture all the social benefits of a given quality increase since individual consumer demands are inelastic. This means that the first of the two effects discussed above disappears and the privately chosen waiting time of the follower is socially excessive when the second introduction represents such a leap in quality that it effectively eliminates the first product from contention. For lower values of research ability compared to time preference, on the other hand, the first effect actually dominates so that t_B is smaller than the social optimum. Overall, then, incremental follow-up innovations tend to be introduced too quickly, while drastic ones tend to be introduced too[9].

A second source of inefficiency is that, given the second mover's optimal reaction, the first innovation can be introduced too early or too late so that t_A can be greater or smaller than t_A^s

---

[7] In other words, $\pi_B^D - 0 \leq SS^D(t_A, t_B) - SS^M(t_B)$

[8] High rates of research ability compared to time preference refers in this case to the range $\frac{\theta}{r} \geq 2.55c$

[9] Other models, cited in our introduction, of cumulative innovation have not exhibited this feature because of restrictions on the nature of competition, either restrictions on the parameter ranges considered or restrictions on the dimensions of differentiation allowed. Our model encompasses sufficient generality to allow this case to emerge.

Proposition 3: Assume that $\theta_A = \theta_B = \theta$. The initial date of introduction, t_A, will be too early compared to the social optimum if the speed of learning is either small (i.e, $1.5c \le \frac{\theta}{r} < 1.8c$) or large enough that the second mover enters with a drastic innovation, (i.e. $\frac{\theta}{r} \ge 2.55c$). The first introduction always occurs too early in a stand-alone equilibrium. For intermediate research abilities, the first product is introduced too late.

Proof: See Appendix

When the rate of research progress (or "ability") is high enough that drastic innovation will follow, the leader's date of introduction tends to be too early. Combining this with our earlier welfare results on the follower, we observe a pattern of sequential monopoly for this parameter range, with the first product introduced socially too early and the follower's product introduced socially too late. On the other hand, when research progress is very slow, both the leader and the follower move socially too fast to market, each with a small improvement. For intermediate ranges, the follower moves socially too quickly, given the leader's introduction date, but the leader may move too quickly or too slowly.

3. Policy Instruments

We have observed that there can be a deviation between the socially and the privately optimal entry date of both the leader and the follower. We now consider two policy instruments that might help reduce this discrepancy. The first instrument, a minimum quality standard, can only retard the date of first entry. It can therefore only be useful over parameter ranges where the leader enters too soon in equilibrium. The second instrument, a novelty requirement, effectively increases the time that elapsed between first and second entry. As such it is useful when the second entrant moves too soon. However, the welfare analysis of the two instruments is more complex than this. By delaying first entry, a minimum quality standard also delays the date of second entry. Similarly, a novelty requirement directly changes the behaviour of the follower, but this in turn also affects the behaviour of the leader.

3.1 Minimum Quality Standards

A binding minimum quality standard forces the first entrant to introduce its product later than it would have wished to. The impact of such a policy over the range where we have a stand-alone equilibrium is straightforward for two reasons. Firstly, a binding minimum quality *cannot change the nature of the equilibrium*. By pushing back the profit-maximising date of first introduction, the policy further decreases the profits of the leader. Since these were already lower than those of the follower, the equilibrium remains of the stand alone variety. Secondly, we already know from proposition 3 that, over the range where stand alone equilibria prevail, the first product is introduced to early. We can therefore conclude that there always is a minimum quality standard that would strictly increase welfare.

We now turn to the parameter range for which we have pre-emptive equilibria. This creates an additional technical difficulty as the policy can itself change the nature of the equilibrium: by decreasing the profits of the first mover it can turn a pre-emptive equilibrium into a stand-alone equilibrium. Taking this potential switch into account we find that there exists a binding quality standard that increases welfare if research abilities are high enough. In particular, welfare increases when abilities are such that the follower would enter with a drastic innovation. These results are summarised in proposition 4.

Proposition 4: Assume that $\theta_A = \theta_B = \theta$. There is a binding minimum quality standard that raises welfare if research abilities are limited ($1.5c < \frac{\theta}{r} < 1.8c$) or when they are large enough that the follower would enter with a drastic innovation ($\frac{\theta}{r} \geq 2.55c$). For intermediate values of research ability, our result depends on the level of research ability: in the range [$1.8c < \frac{\theta}{r} < 2.19c$] the minimum quality standards cannot be used to improve welfare, while for range [$2.19c < \frac{\theta}{r} < 2.55c$], the minimum quality standard can improve welfare.

Proof: See Appendix

3.2 Novelty Requirements

Following Scotchmer and Green (1990) and O'Donoghue (1998) we interpret a novelty requirement as a restriction on the vertical scope of patents. In other words, a follower must demonstrate a minimum improvement over the initial (patented) product to be allowed to exploit its own product commercially. However, our approach departs from the existing literature in that we do not assume that the innovations of the two firms are "cumulative" in the traditional sense of the term. Cumulative innovation refers to situations where the second innovation or "improvement" would not be possible without the prior development of the first innovation. There is therefore an exogenously determined sequence of investment, with investment on the follow-up innovation starting only once the initial innovation has been obtained. By contrast, in our model both firms "race" from the beginning and the timing of both introductions as well as the identity of first and second innovators are determined endogenously. This is still consistent with a novelty requirement as an interpretation, but it means that the order of entry is not "set" beforehand. As we will see, this leads to rather different conclusions.

A binding novelty requirement has several effects on the equilibrium timing of entry. Firstly, it delays the introduction of the second product. When we have very high research ability in the industry, this effect does not improve welfare as the follower already waits socially too long to introduce (proposition 2). This occurs over the range where the second innovation is drastic. In other words, the incentive to improve quality to the point of dominating the industry is so powerful that a novelty requirement is not necessary. Indeed, as incentives to wait are already excessive, any binding novelty requirement would in fact decrease both the profits of the second mover and welfare. It would however increase the profits of the initial innovator since it increases the length of its monopoly period. For lower research abilities, we know that the second product is introduced to quickly so that a novelty requirement can be used to increase welfare.

By delaying second entry beyond the profit-maximising date, a binding novelty requirement decreases the profits of the second mover. By the same token, it also increases the profit of the first mover, for any *given* date of first introduction, since it extends the length of its monopoly period. These effects have quite different consequences depending on the type of equilibrium involved. In a stand-alone equilibrium a binding novelty requirement makes the leader wait longer as the value of quality improvements can be enjoyed over a longer monopoly phase. Since initial entry occurs to early over this range (proposition 3), this effect improves welfare. It also ensures that – as in the previous literature – a binding novelty requirement increases the profits of the initial innovator and decreases those of the follower. The situation is quite different over the range where pre-emptive equilibria arise. Precisely because it increases the profit of the leader and decrease those of the follower *for a given date of first introduction*, the novelty requirement leads to faster introduction by the leader: starting from an initial equilibrium where the profits of the two firms are equal, firms will compete to introduce even earlier in order to eliminate the discrepancy between leader and follower's profits resulting from the novelty requirement. This increases welfare for intermediate values of the research ability parameter but decreases as soon as we hit the range where θ/r is large enough to guarantee that the follower enters with a drastic improvement. More notably, though, in a pre-emption equilibrium[10], *a binding novelty requirement ends up decreasing the profits of both the follower and the initial inventor*. Putting these effects together give us the results presented in proposition 5.

Proposition 5: Assume that $\theta_A = \theta_B = \theta$. If $\frac{\theta}{r} \geq 2.55c$ then any binding novelty requirement decreases welfare. For $1.5c < \frac{\theta}{r} < 1.8c$, there exists a binding novelty

[10] Starting from a pre-emption equilibrium the game will remain in a pre-emption equilibrium for any binding novelty requirement. On the other hand, a binding novelty requirement can change a stand alone equilibrium into a pre-emptive equilibrium. This technical difficulty is taken into account when deriving the results in proposition 5.

requirement which improves welfare. For $\frac{\theta}{r} > 1.8c$, any binding novelty requirement decreases the profits of both the follower and the initial inventor and speeds up the date of initial entry.

Proof: See appendix

The last part of the proposition implies, perhaps counter-intuitively, that for the range over which pre-emptive equilibria arise, a binding socially optimal novelty requirement decreases both the R&D investment and the profits of the first mover. Making (patent) protection of the first innovation "stronger" does not therefore necessarily make the first mover better off, nor does it necessarily increase its R&D investment. The intuition for the desirability of "weak" patents is that the novelty requirement lowers the "opportunity cost" of being a follower and so allows for the leader to pre-empt earlier with a lower-quality product. This ends up being bad for the leader, but as the alternative of moving later is also less attractive, this worse alternative can still be the optimal choice for the firm. This argument is quite distinct from previous arguments against strong patent in the burgeoning literature on weak patents[11]. Another interesting feature of this analysis is that it indicates that welfare can move quite discontinuously with policy due to discontinuities in the behaviour of the following firm. As research ability falls to the point where innovation is no longer drastic, the follower's introduction time moves discontinuously from "too late" to "too early". This can discontinuously increase the benefit of imposing a binding novelty requirement. Furthermore, the sudden disappearance of the negative effect of

[11] Weak patents have been found to improve profits and welfare under conditions where other frictions guarantee the profitability of firms (see Cohen and Levinthal (1989) for an early contribution in this vein) or, when added to frictions, weak appropriability can increase the chance of discovery, the value to final consumers and, hence, the profits of all firms that can capture this value (Bessen and Maskin (2007)).

thee novelty requirement on the first introduction as we pass from pre-emptive to stand alone equilibrium again makes welfare jump at this point in response to the policy.

4. Asymmetric Abilities

In this section, we comment on how our results change when we allow the two firms to differ in their "abilities", θ_A and θ_B. This can reflect the firms' differential endowment of the human capital necessary to adopt publicly available technology or it can result from the fact that the different research routes which were chosen by the firms initially prove to be more or less amenable to quick development. Perhaps more interestingly, we could think of different abilities' resulting from different process innovations that allow access to different technological paths. In other words, while in the previous section we considered a policy instrument of changing the scope of protection on product innovation, here we consider how protection of process innovations, which could result in differences in the speed with which developments can be made to products, affect our results. These differences in process need not be thought of as patentable process innovations. They could instead be differences in innovation systems or architectures within firms that allow quicker or slower progress in quality.

When firms have different levels of ability, the lag between the two introduction dates depends on the difference in ability between the two firms. For the purposes of comparison with the symmetric case, we state the formal expression describing the follower's behaviour here:

Lemma 4: The entry date of the follower, $t_i(t_j)$, in response to the leader's entry date, t_j, can be described as follows:

For $\theta_i > 2.55cr$ $\quad t_i(t_j) = t_j + (1/r) + c/\theta_i + [(\theta_j-\theta_i)/\theta_i]t_j$

For $1.5cr < \theta_i < 2.55cr$ $\quad t_i(t_j) = t_j + (2/r) - 3c/\theta_i + [(\theta_j-\theta_i)/\theta_i]t_j$

Proof: The proof is not included as it differs only trivially from the proof of Lemma 1.

Notice that now, when the less able firm moves first so that $\theta_j < \theta_i$, the follower's entry date moves forward as its *relative* ability increases. The follower's entry date also decreases with its own *absolute* level of ability, so that a more able follower moves earlier all else equal. There is a discrete change in the entry behaviour of the follower when the ability level passes a threshold level. At this point, the follower discretely increases her waiting time and introduces a drastic product innovation.

In the pre-emptive equilibrium, just as in the symmetric case, one firm introduces first just before its rival would want to become first mover. There is no necessary correlation, however, between ability and order of entry. Indeed, for the parameter range where a pre-emption equilibrium exists, the least able firm introduces first when abilities are rather high whereas the more able firm moves first when abilities are rather low. In the first case, the quality of the leader's good must be lower than the quality of the product introduced by its more proficient competitor. It is also true that the less able second mover always introduces a product of higher quality than the more efficient leader in equilibrium in the second case, as only in this case can the discounted profits of leader and follower be the same. Hence, while quality increases over time, the "intrinsic" ability of the leader may be higher or lower than that of the follower. It is also the case that for stand alone equilibria, either the high ability firm or the low ability firm may move first, depending on the parameter values. This is summarised in the proposition, below:

Proposition 6: Parameter ranges exist for which the most able firm enters the market firm as well as parameter ranges for which the least able firm moves first.

Proof: See Appendix

Allowing for differences in the firms' abilities modifies the analysis of minimum quality requirements on two counts. First, a binding minimum quality standard can change the order of introduction of the two products. In other words, it can change the identity of the leader from a high to a low ability firm (or vice versa). We now illustrate this effect with the following proposition:

Proposition 7: If the parameter range is such that the lower quality firm enters first, then a binding minimum quality standard can reverse the order in which the two firms choose to introduce their product.

Proof: See Appendix

This effect allows the minimum quality standard to have an effect of generating relatively early participation in the market of a high ability firm. All else equal, this will benefit welfare. Unfortunately, and contrary to the symmetric case, a minimum quality standard now also affects the delay between first and second introductions. Furthermore, the direction and magnitude of the effect depends on whether the more or less able firm moves first as well as on the absolute level of ability of the following firm. When we switch the order so that the more able firm moves first, the effect on the follower's date, all else equal, is to delay entry. Hence, while the minimum quality standard obtains the desired quality from a high ability firm, it does not necessarily increase overall welfare because it can delay improvements to that quality. Finally, the initial date of introduction now enters into the expression for the delay in the follower's introduction, with a coefficient that increases with the difference in the relative abilities of the leader and follower. As a result, a minimum quality standard, by pushing back the entry date of the leader, can have a feedback effect on the entry date of the follower.

In sum, adding the effect of the minimum quality standard on both the leader and follower delays, one sees that the welfare effect of a minimum quality standard can depend crucially on the spread of research abilities of the firms involved, which firm moves first in the initial equilibrium without the policy, and the type of equilibrium that prevails. In general, the overall welfare effect is unclear. To illustrate, consider the case of proposition 6 where the lower quality firm enters first in a pre-emption equilibrium. Starting from a point where research abilities are very close to equal, let a mean-preserving spread in abilities occur. This tends to decrease the follower's waiting time, from lemma 4 so that the pattern of entry is for a low ability firm to enter first, followed quickly by an improved quality offered by the high ability firm. When we introduce a binding minimum quality standard, we reverse the order of entry, now having a high ability firm enter first, followed by the low ability firm entering with higher quality but after a long wait. One cannot, in general, rank the welfare outcomes of these two possibilities, nor can one make any definitive statements that a minimum quality standard improves welfare overall. Indeed, this is true of the novelty requirement as well in this framework[12].

5. Discussion and Conclusions

We have investigated the timing of entry in a duopoly framework where two firms may independently improve the quality of the product they introduce to market. Our model is stylised, but captures some important features of innovation markets, including emphasising the importance of incremental innovation and allowing for different research streams targeted to the needs of different types of consumers. We derive a number of results on how entry behaviour changes as the research ability of the firms changes.

Considering first the case of symmetric “research abilities”, we find that discontinuous changes in introduction dates can occur as we vary this parameter so as to move from “pre-emptive” to “stand alone” equilibrium. We also observe differences in the social optimality of entry depending on research ability. When research ability is low, follower innovations tend to be introduced too quickly – and have too low quality compared to the social optimum -- whereas when research ability is high, they tend to be introduced socially too slowly. Conversely, high ability leaders tend to introduce innovations too quickly and at socially too low quality. Minimum quality standards can play a role in correcting this early movement of leaders. Novelty requirements have a place in correcting early movement of followers. However, we find that even a welfare increasing novelty requirement does not necessarily increase the profits or investment levels of the initial inventor. So,

[12] More detailed discussion is included within the proofs of propositions 6 and 7 for specific parameter ranges and entry date rankings.

stronger patent protection can hurt both leader and follower even if it improves welfare. The reason for this is that the stronger patent constrains the profits of the follower, so that the alternative to being a leader is worse. As a result, firms get into a pre-emptive race to be first, which lowers profit and generates earlier (and hence lower quality) introduction. This reason does therefore crucially depend on the fact that both the timing of entry and the identity of the first mover are determined endogenously in our model, contrary to the rest of the literature.

When we allow research abilities to differ we show, like Riordan (1990), that higher ability firms need not be the first movers or the higher quality providers in the market. Indeed, they may be either. With asymmetric firms, the effects of binding minimum quality standards are more complex as policy intervention can actually change the order of entry of the two firms. Such change has ambiguous welfare consequences. If the effect is to turn a high ability firm from a follower to a leader, the welfare effect tends to be positive. The welfare effect of the standard depends on both the level and the spread of research abilities in this case. Minimum quality standards are most likely to be effective if the firms are reasonably evenly matched in terms of research ability and if these abilities are either fairly limited or very high. Novelty requirements can also change the order of entry and have ambiguous welfare consequences.

References

Argenziano, R., and P. Schmidt-Dengler (2009). "Preemption and the Efficiency of Entry", University of Essex mimeo.

Beath, J., Y. Katsoulacos, and D. Ulph (1987). "Sequential Product Innovation and Industry Evolution", *The Economic Journal*, 97(388a), 32-43.

Bessen, J., Maskin, (2007) "Sequential Innovation, Patents and Innovation", *The RAND Journal of Economics*, forthcoming.

Boom, A. (1995). "Asymmetric International Minimum Quality Standards and Vertical Differentiation", *Journal of Industrial Economics*, 43(1), 101-119.

Choi, J. P. (1993). "Dynamic R&D Competition, Research Line Diversity, and Intellectual Property Rights", *Journal of Economics and Management Strategy* Summer, 2(2), 277-297.

Cohen, W., and D. Levinthal (1989). "Innovation and Learning: The Two Faces of R&D", *The Economic Journal* 99(397), 569-596.

Crampes, C., and A. Hollander (1995.) "Duopoly and Quality Standards", *European Economic Review* 39(1), 71-82.

Dasgupta, P., and J. Stiglitz (1980). "Uncertainty, Industrial Structure and the Speed of R&D", *Bell Journal of Economics* 11(Spring), 1-8.

Dutta, P., S. Lach, and Al. Rustichini (1995). "Better Late than Early: Vertical Differentiation in the Adoption of a New Technology", *Journal of Economics and Management Strategy* 4(4), 563-589.

Fudenberg, D., and J. Tirole (1985.) "Preemption and Rent Equalization in the Adoption of New Technology", *Review of Economic Studies* 52, 383-401.

Gallini, N. (1992). "Patent Policy and Costly Imitation", *Rand Journal of Economics* 23(spring), 52-63.

Gilbert, R., and C. Shapiro (1990). "Optimal Patent Length and Breadth", *Rand Journal of Economics* 21(1), 106-113.

Gruber, H. and F. Verboven (2001). "The Evolution of Markets under Entry and Standards Regulation – the Case of Global Mobile Telecommunications", *International Journal of Industrial Organisation* 19, 1189-1212.

Harris, C., and J. Vickers (1987). "Racing with Uncertainty", *Review of Economic Studies* 54(1), 193-209.

Herguera, I., and S. Lutz (1998). "Oligopoly and Quality Leapfrogging", *The World Economy* 21(1), 75-94.

Hopenhayn, H., and M. Mitchell (2001). "Innovation Variety and Patent Breadth", *RAND Journal of Economics* 32(1), 152-166.

Hopenhayn, H., G. Llobet, M. Mitchell (2006). "Rewarding Sequential innovators: Prizes, Patents and Buyouts", *Journal of Political Economy* 114(6), 1041-1068.

Katz, M., and C. Shapiro (1987). "R&D Rivalry with Licensing or Imitation", *American Economic Review*, 77(3), 402-420.

Klemperer, P. (1990). "How Broad Should the Scope of Patent Protection Be?" *Rand Journal of Economics* 21(1), 113-131.

Kuhn, M., (2007). "Minimum Quality Standards and Market Dominance in Vertically Differentiated Duopoly", *International Journal of Industrial Organization* 25(2), 275-290.

Lee, T., and L. Wilde (1980). "Market Structure and Innovation: A Reformulation", *Quarterly Journal of Economics*, 94(2), 429-436.

Lippman, S., and J. Mamer (1993). "Preemptive Innovation", *Journal of Economic Theory* 61(1) 104-119.

Loury, G. (1979). "Market Structure and Innovation", *Quarterly Journal of Economics*, 93(3), 395-410.

Manski, C. (2009). "Adaptive Partial Drug Approval: A Health Policy Proposal", *The Economist's Voice* 6(4), article 9.

Matutes, C., P. Regibeau and K. Rockett (1996). "Optimal Patent Design and the Diffusion of Innovations", *Rand Journal of Economics*, 27(1), 60-83.

Motta, M., and J-F Thisse (1993). "Minimum Quality Standards as an Environmental Policy: Domestic and International Effects" Nota di Lavoro 20.93 Fondazione Eni Enrico Mattei, Milan.

O'Donoghue, T. (1998). "A Patentability Requirement for Sequential Innovation", *RAND Journal of Economics* 29(4), Winter, 654-679.

Quint, D., and L. Einav (2005). "Efficient Entry", *Economics Letters* 88, 278-283.

Reinganum, J. (1981). "On the Diffusion of New Technology: A Game-Theoretic Approach", *Review of Economic Studies*, 48(3), 395-405.

Reinganum, J., (1989). "The Timing of Innovation: Research, Development and Diffusion", in R. Schmalansee and R. Willig, Eds., *Handbook of Industrial Organization*. New York: North-Holland.

Riordan, M., (1992). "Regulation and Pre-emptive Technology", *Rand Journal of Economics* 23(3), 334-349.

Ronnen, U. (1991). "Minimum Quality Standards, Fixed Costs and Competition", *RAND Journal of Economics* 22(4), 490-504.

Scarpa, C. (1998). "Minimum Quality Standards with More than Two Firms", *International Journal of Industrial Organization* 16(5), 665-676.

Scotchmer, S., and J. Green (1990). "Novelty and Disclosure in Patent Law", *Rand Journal of Economics* 21(1), 131-146.

Scotchmer, S., (1996). "Protecting Early Innovators: Should Second Generation Products be Patentable?" *Rand Journal of Economics*, 27(2), 322-331.

Vickers, J. (1996). "The Evolution of Market Structure when there is a Sequence of Innovations" *Journal of Industrial Economics* 35(1), 1-12.

See http://www2.dse.unibo.it/wp/235.pdf and http://www2.dse.unibo.it/wp/427.pdf http://www2.dse.unibo.it/wp/532.pdf for more references also http://aic.ucdavis.edu/publications/MQSandWelfare.pdf

Full Appendix

Sketch of Proofs for Preliminary results on which Propositions will build:

First, it can be shown that all profit functions have a unique maximum as a function of the time of introduction. This is important to the results that follow. Second, we will assume in our methodology for the proofs that follow that we are working with a finite, but arbitrarily fine time grid. It will also simplify notation considerably to choose a grid such that all relevant critical points fall precisely on the grid.

Sketch of Proof of Lemma 1: Deriving the time of entry of the follower

Define: $\varphi \equiv t_i^f - t_j, \pi_{ia} \equiv \frac{e^{-rt}}{r}\frac{c}{2}[1+\frac{\theta\varphi}{3c}]^2$ and $\pi_{ib} \equiv \frac{e^{-rt}}{r}(\theta\varphi - c)$. In other words, the best response following lag will be denoted φ, while the profits denoted *a* and *b* are the profits of the follower, assuming that she shares the market or appropriates the entire market, respectively . Note that argmax $\pi_{ia} \equiv \varphi_a = \frac{2}{r} - \frac{3c}{\theta}$ and argmax $\pi_{ib} \equiv \varphi_b = \frac{1}{r} + \frac{c}{\theta}$. Hence, the date that maximises the follower's profit differs, depending on whether we assume she waits long enough to appropriate the entire market or not. As π_{ia} is the correct profit function only for $\theta\varphi_a \leq 3c$, we can substitute for φ_a to assert that φ_a is a candidate best response only if $\frac{\theta}{r} < 3c$. Similarly, π_{ib} is the correct profit function only for $\theta\varphi_b > 3c$ so that, also by substitution, φ_b is a candidate best response function only if $\frac{\theta}{r} \geq 2c$. It is also the case that if $\frac{\theta}{r} < 1.5c$, the follower is never willing to wait once the first product is introduced. Since $\varphi_a \geq \varphi_b$ if and only if $\frac{\theta}{r} \geq 4c$, we must consider four cases.

Case 1: $\frac{\theta}{r} \geq 4c$. As $\varphi_a > \frac{3c}{\theta}$, the maximum of π_{ia} over the range for which this is a candidate best response, $\varphi \leq \frac{3c}{\theta}$, is $\varphi = \frac{3c}{\theta}$, while the maximum of π_{ib} over $\varphi \geq \frac{3c}{\theta}$ is φ_b. Since $\pi_{ib}(\varphi_b) > \pi_{ib}(\frac{3c}{\theta}) = \pi_{ia}(\frac{3c}{\theta})$, the best response is $\varphi_i = \varphi_b$. Hence, for this parameter range the follower chooses to wait so as to develop a drastic product innovation.

Case 2: $3c \leq \frac{\theta}{r} < 4c$ is the same as case 1.

Case 3: $2c \le \frac{\theta}{r} < 3c$. As $\varphi_a < \frac{3c}{\theta}$, φ_a maximises π_{ia} over $\varphi \le \frac{3c}{\theta}$ while φ_b maximises π_{ib} over $\varphi > \frac{2c}{\theta}$. To determine the follower's best response, we must compare $\pi_{ia}(\varphi_a)$ and $\pi_{ib}(\varphi_b)$. Substituting and solving, we have $\pi_{ib}(\varphi_b) > \pi_{ia}(\varphi_a)$ if and only if $\frac{\theta}{r} > \frac{9c}{2} e^{-\frac{4rc}{\theta}}$ or $\frac{\theta}{r} > 2.553c$. In other words, for $\frac{\theta}{r} > 2.553c$ it is best for the follower to wait and appropriate the entire market rather than share. In other words, in this case the follower (endogenously) chooses to develop a drastic innovation. For parameter ranges below this, the follower chooses to develop an incremental innovation.

Case 4: $\frac{3c}{2} < \frac{\theta}{r} < 2c$. Over this range, φ_a maximises π_{ia} over $\varphi \le \frac{3c}{\theta}$, while the maximum of π_{ib} over $\varphi < \frac{3c}{\theta}$ occurs at $\varphi = \frac{3c}{\theta}$. Since $\pi_{ia}(\varphi_a) > \pi_{ia}(\frac{3c}{\theta}) = \pi_{ib}(\frac{3c}{\theta})$, the best response is $\varphi_i = \varphi_a$. In other words, the follower chooses to develop an incremental innovation over this range. ■

Summarising, then, we have a range over which the follower chooses to wait to develop a drastic innovation, $\frac{\theta}{r} > 2.553c$, and a range over which the follower endogenously chooses to be an incrementalist $1.5c < \frac{\theta}{r} \le 2.553c$.

Lemma 2: (Deriving the entry time that maximises the discounted payoffs, without pre-emption) For the symmetric case, we have:

$$t_{jmax} = \begin{cases} \frac{1}{r} + \frac{c}{\theta} & \text{if } \frac{\theta}{r} \ge 2.55c \\ \frac{1}{r} + \frac{c}{\theta} - \frac{2c}{\theta}\frac{Y}{1-Y}[1 - \frac{\theta}{3rc}]^2 & \text{if } 1.5c < \frac{\theta}{r} < 2.55c \end{cases}$$

where $Y = e^{-2} e^{\frac{3rc}{\theta}}$

Lemma 3: (Deriving the pre-emption date) For the symmetric case, we have:

$$t_p = \begin{cases} \frac{c}{\theta} + \frac{1}{r}\frac{e^{-1}e^{\frac{-rc}{\theta}}}{1 - e^{-1}e^{-\frac{rc}{\theta}}} & \text{if } \frac{\theta}{r} \ge 2.55c \\ \frac{c}{\theta} + \frac{2c}{\theta}\frac{Y}{1-Y}[\frac{2\theta}{3rc} - 1] & \text{if } 1.5c < \frac{\theta}{r} < 2.55c \end{cases}$$

Sketch of Proof of lemma 2 and lemma 3 (for the symmetric case)

Four cases must be analysed since the profit function can take one of two forms during the monopoly period and one of two forms during the duopoly period.

Case 1: $\frac{\theta}{r} \geq 2.55c$ and $t_j > \frac{2c}{\theta}$. In this case, $t_{j\max} = \frac{1}{r} + \frac{c}{\theta}$ which satisfies the assumption that $t_j > \frac{2c}{\theta}$. Setting $\pi_j^1(t_j) = (\frac{\theta t_j - c}{r})e^{-rt_j}(1 - \frac{e^{-\frac{rc}{\theta}}}{e})$ equal to $\pi_i^f = \frac{1}{r}\frac{\theta}{r}e^{-rt_i}\frac{e^{\frac{-rc}{\theta}}}{e}$ yields the pre-emption time $t_p = \frac{c}{\theta} + \frac{1}{r}[\frac{e^{\frac{-rc}{\theta}-1}}{1 - e^{\frac{-rc}{\theta}-1}}]$. Also, $t_{j\max} > t_p$ since $e^{\frac{-rc}{\theta}} < \frac{e}{2}$ for $\frac{\theta}{r} \geq 3c$.

Case 2 : $\frac{\theta}{r} \geq 2.55c$ and $t_j \leq \frac{2c}{\theta}$. This case cannot arise in equilibrium because t_{imax} still is greater than t_p and $t_p = \frac{2}{\theta}[c\frac{\theta}{r}[\frac{e^{\frac{-rc}{\theta}-1}}{1 - e^{\frac{-rc}{\theta}-1}}]]^{\frac{1}{2}} > \frac{2c}{\theta}$.

Case 3: $2c \leq \frac{\theta}{r} \leq 2.55c$ and $t_j > \frac{2c}{\theta}$. In this case,
$t_{j\max} = \frac{1}{r} + \frac{c}{\theta} - 2(\frac{c}{\theta})Y(1 - \frac{\theta}{3rc})^2/(1 - Y)$, where $Y = e^{-2}e^{\frac{3rc}{\theta}}$. Setting $\pi_j^1 = \frac{1}{r}e^{-rt_i}[(\theta t_j - c)(1 - Y) + 2cY(1 - \frac{\theta}{3rc})^2]$ equal to $\pi_i^f = 2\frac{c}{r}[\frac{\theta}{3rc}]^2 Ye^{-rt_j}$ yields $t_p = \frac{c}{\theta} + \frac{2c}{\theta}\frac{Y}{1-Y}[\frac{2\theta}{3rc} - 1]$. Also, $t_{j\max} > t_p$ if and only if $\frac{\theta}{r}[\frac{Y}{1-Y}] < \frac{9c}{2}$. To see that this condition is satisfied for the range we consider in this case, notice that for $\frac{\theta}{r} \in [2c, 3c]$, $\frac{Y}{1-Y} \in [0.582, 1.541]$. Indeed, note that for $\frac{\theta}{r} \in [\frac{3c}{2}, 2c]$, $\frac{Y}{1-Y} \in [1.541, \infty[$, so that t_{jmax} must be smaller than t_p for low enough values of $\frac{\theta}{r}$. Numerical computations show that this occurs for $\frac{\theta}{r} \leq 1.804$.

Case 4: $2c \leq \frac{\theta}{r} \leq 2.55c$ and $t_j \leq \frac{2c}{\theta}$. This case cannot occur because $t_p < t_{jmax}$ and $t_p = \frac{2c}{\theta}\{2\frac{Y}{1-Y}[\frac{2\theta}{3rc} - 1]\}^{\frac{1}{2}}$, which is greater than $\frac{2c}{\theta}$ because, for $2c \leq \frac{\theta}{r} \leq 2.55c$, $2\frac{Y}{1-Y}[\frac{2\theta}{3rc} - 1] > 1$.

Lemma 4: For the asymmetric case, we have expressions for the behaviour of the follower:

$$t_i^f(t_j^l) - t_j^l = \frac{1}{r} + \frac{c}{\theta_i} + \frac{\theta_j - \theta_i}{\theta_i} t_j^l \quad \text{for } \frac{\theta_i}{r} \geq 2.55c$$

$$= \frac{2}{r} - \frac{3c}{\theta_i} + \frac{\theta_j - \theta_i}{\theta i} t_j^l \quad \text{for } \frac{\theta_i}{r} < 2.55c$$

As the proof of this case differs trivially from the proof of lemma 1, the proof will be omitted (but is available from the authors upon request). Notice that the lag in introduction dates now depends on the difference in ability between the two firms.

Sketch of Proof of Proposition 1 -- the equilibrium entry dates -- including elements of proposition 6.

Let (*x,y*) denote the decisions of each of the players at any time, *t*, where 0 indicates a decision to stop and 1 indicates a decision to continue development. Furthermore, let G^0 denote the full game and G^t denote the subgame that starts at time *t.*

For a moment, consider the full asymmetric case, where $\theta_A < \theta_B$. Four critical points will be important to the proofs that follow. First, t_{pA} represents the time where the payoff to firm *A* from stopping -- at some time, *t* -- before firm *B* is equal to its payoff from stopping after firm *B* has stopped – at some time, *t*. In other words, *A* would be willing to pre-empt back to this date, but at no earlier date. Second, point t_{pB} represents the time when the payoff to firm *B* from stopping before firm *A* is equal to its payoff from stopping after firm *A* has stopped. In other words, this is the analogous earliest pre-emption date for firm *B*. Third, point t_{Amax} represents the time when the payoff to firm *A* from stopping first is maximised. Finally, point t_{Bmax} represents the time when the payoff to firm *B* from stopping first is maximised. Our first case, which we will fully develop, is the case where $\theta_A < \theta_B$ and $t_{pA} < t_{pB} < t_{Amax} < t_{Bmax}$. Indeed, the argument for this case is completely analogous to the symmetric case of $t_p < t_{max}$. We will make the argument for the full asymmetric case, as this can also serve to form the basis for proposition 6, but keep in mind that the argument is the same as for the analogous symmetric case. Of course, for the asymmetric case, we can have $t_{pB} > t_{Amax}$ so that we have $t_{pA} < t_{Amax} < t_{pB} < t_{Bmax}$ as well when $\theta_A < \theta_B$. We consider this latter case more briefly, below.

To anticipate our conclusions, and again using the phrasing for the asymmetric case, if $t_{pA} < t_{pB} < t_{Amax} < t_{Bmax}$ we will show that the following outcome is a unique subgame perfect equilibrium outcome for the full game, G^0: both firms wait until time t_{pB}. Then, firm *A* stops the R&D phase at t_{pB}. Firm *B* stops its research later, at $t_B^*(t_{pB})$. For the corresponding symmetric case where $t_p < t_{max}$, there are two such outcomes that differ only in the identity of the firm that moves first. In other words one firm, firm *A* (firm *B*) stops the R&D phase at t_p, while the other, firm *B* (firm *A*) stops its research later at $t^*(t_p)$. These are the "pre-emption equilibrium" equilibria in the text.

We can also have the case where $t_{Amax} < t_{Bmax} < t_{pB} < t_{pA}$. In this case, the unique subgame perfect equilibrium outcome for the full game, G^0 is that firm *A* moves first at t_{Amax} if and only if $\pi^l_A(t_{A\max}) \geq \pi^f_A(t_{B\max})$ while firm *B* moves first at t_{Bmax} if and only if $\pi^l_A(t_{A\max}) < \pi^f_A(t_{B\max})$. In the analogous symmetric case where t_{max} is smaller than t_p, we will show that there are two subgame perfect equilibrium outcomes for the full game, G^0. In each of these, both firms wait until the time t_{max}. One of the two firms, firm *A* (firm *B*), stops the R&D phase at t_{max} while the other, firm *B* (firm *A*), stops its research later at $t^f(t_{max})$. These are the "stand alone" equilibria in the text.

Case I: $t_{Amax} > t_{pB}$

The profit function of the leader has a unique maximum and the profit function of the follower is decreasing in the date of introduction by the leader.

Necessary conditions:

First, we show that if the strategy combination is a subgame perfect equilibrium for G^0, then the following local strategy combinations must be a part of it:

$$(s^t_A, s^t_B) = \begin{cases} (1,1) \text{ for } t=0,\ldots..,t_{pB}-1 \\ (0,1) \text{ for } t=t_{pB}. \end{cases} \qquad \text{(i)}$$

Consider the behaviour of the firms in periods $0,\ldots,t_{Amax}$. At least one firm must stop its research not later than t_{Amax}. Indeed, if firm B did not stop, then it would be the best response for firm A to stop its research at t_{Amax} simply from the definition of t_{Amax} as the time that maximises A's discounted payoffs when it is the first to stop. Thus (1,1) for $t=(0,\ldots,t_{Amax})$ cannot be part of the equilibrium local strategies for G^0.

Similarly, the local strategy (0,0) at any time $t \leq t_{A\max}$ cannot be a part of a subgame perfect equilibrium for G^0, because firm A can increase its payoff from the subgame G^t by changing its local strategy to 1. Thus, in a subgame perfect equilibrium for G^0, the local strategies (0,1) or (1,0) are played at some time, t, where $(0 \leq t \leq t_{A\max})$. Denote by t^* the smallest t for which (0,1) or (1,0) is an equilibrium local strategy.

We show that $t^* = t_{pB}$. It is a dominant strategy for firm B not to stop first before time t_{pB} since t_{pB} is defined as the time at which first mover and second mover profits are equal. Since the first mover payoff to firm A is increasing in the interval $[0, t_{pB}]$, the best response of firm A is to stop not earlier than t_{pB}. Thus, $t^* \geq t_{pB}$. Suppose that $t^* > t_{pB}$. We consider two possible cases:

Case 1: (0,1) is played at t^*. Again, from the definition of t_{pB}, firm B would do better by stopping one period before t*, which is greater than or equal to t_{pB}. Thus, the local strategy (0,1) at $t^* > t_{pB}$ is not a part of a subgame perfect equilibrium.

Case 2: (1,0) is played at t^*. In this case firm A would do better by stopping one period earlier, at $t^* - 1$, which is greater than or equal to t_{pA}. Again, this follows from the definition of t_{pA}. Thus, the local strategy (1,0) at t^* is not a part of a subgame perfect equilibrium.

Hence, t^* must be equal to t_{pB}.

Finally, the pair (1,0) cannot be an equilibrium local strategy combination at $t^* = t_{pB}$. Suppose, to the contrary, that (1,0) at $t^* = t_{pB}$ is played in a subgame perfect equilibrium. Then firm A can do better by playing (0,1) at $t_{pB} - 1$, which is greater than or equal to t_{pA}. (In other words, rather than simply letting firm B pre-empt, it would be better for firm A to be the first mover. As we have not "rolled back the game" to A's earliest pre-emption date, A should prefer this.) Hence, the local strategy combination given by (i) must be a part of any subgame perfect equilibrium for G^0.

Sufficient Conditions

Now, we show that the following strategy combination is a subgame perfect equilibrium:

$$(s_A^t, s_B^t) = \begin{cases} (1,1) \text{ for } t=0,\ldots,t_{pB}-1 \\ (0,1) \text{ for } t=t_{pB}, t_{pB}+2, \ldots \\ (1,0) \text{ for } t=t_{pB}+1, t_{pB}+3,\ldots \end{cases} \tag{ii}$$

Consider a subgame G^t for $t=t_{pB}+1$, $t_{pB} + 3$, …. Firm A's payoff from the subgame G^t under the strategy combination listed above in (ii) is $\pi_A(t_A^*(t),t)$. In other words, it is the maximum payoff firm A can obtain given that firm B stopped at time t. Firm B's payoff from the subgame G^t under the strategy combination (ii) is $\pi_B(t,t_A^*(t))$. In other words, it is the maximum payoff firm B can obtain given that firm A stops at time t+1 if firm B would fail to stop at t. Thus the strategy combination (ii) induces a Nash equilibrium on every subgame of G^t for $t=t_{pB}+1$, $t_{pB}+3$…. Similarly, the strategy combination (ii) induces a Nash equilibrium on every subgame of G^t for $t=t_{pB}$, $t_{pB}+2$….

Now consider a subgame G^t for $0 \le t \le t_{pB}$. Firm A's payoff from the subgame G^t under the strategy combination (ii) is $\pi_A(t_{pB},t_B^*(t_{pB}))$. In other words, it is the payoff from stopping no sooner than t_{pB} and inducing the optimal response of firm B. No greater payoff can be obtained, for two reasons. First, stopping earlier would only bring a lower payoff for firm A since its payoffs increase over this range of times as a first mover. In other words, A can pre-empt successfully before time t_{pB}, given that $t_{pA}<t_{pB}$, but it would prefer to pre-empt as late as possible. Second, given that firm B stops at time $t_{pB}+1$ if firm A would fail to stop at t_{pB}, firm A would be transformed into a follower and would earn a lower payoff. Firm B's payoff from the subgame G^t under the strategy combination (ii) is $\pi_B(t_{pB},t_B^*(t_{pB}))$. This cannot be increased given that firm A stops at time t_{pB}. If firm B stops earlier it would get only a lower payoff, as t^* is the optimal following time (and stopping at the same time is never optimal).

We have shown that the strategy combination (ii) induces a Nash equilibrium on every subgame of G^0, thus it is a subgame perfect equilibrium.

For the symmetric case, we make the same argument but eliminate the "A" and "B" designations from the subscripts. In other words, we could specify the strategy combination (iii), below for the symmetric case:

$$(s_A^t, s_B^t) = \begin{cases} (1,1) \text{ for } t=0,\ldots,t_p-1 \\ (0,1) \text{ for } t=t_p, t_p+2, \ldots \\ (1,0) \text{ for } t=t_p+1, t_p+3,\ldots \end{cases} \quad \text{or}\ldots \quad \begin{cases} (1,1) \text{ for } t=0, \ldots, t_p-1 \\ (1,0) \text{ for } t=t_p, t_p+2, \ldots \\ (0,1) \text{ for } t=t_p+1,t_p+3\ldots \end{cases} \qquad \text{(iii)}$$

Either firm could be the first one to pre-empt, with the other firm following at a later date. Hence, for the symmetric case we have two equilibria, characterised by one firm stopping first at t_p while the other continues on and stops at a later date, $t^*(t_p)$.

Case II: $t_{Amax} < t_{pB}$

As was stated above, this case will be dealt with much more briefly than case I. As in case I, this case has analogous arguments for the symmetric and asymmetric cases.

Hence, let $\theta_A < \theta_B$ and the ranking $t_{Amax}<t_{Bmax}<t_{pB}<t_{pA}$ prevail. Then note the following:

Step 1: The two firms never stop at the same date. This follows immediately from lemma 4.

Step 2: $t_{Bmax} < t_{pB}$. If the game reaches t_{Bmax}, then we know that B stops from the definition of t_{Bmax}. Notice that from t_{pB} on, firm B's dominant strategy is to stop since the leader's profit is falling and the follower's profit is less than the leader's. Hence, if the game ever reaches t_{pB}, B stops as well. Given this, and the assumed ranking of dates, if consider a fine but discrete grid, at $t_{pB} - 1$, A waits and B stops. Further, and following similar reasoning, at $t_{pB} - 2$, A waits and B stops. This argument can be repeated so that the game unfolds backwards until we reach t_{Bmax}.

Step 3: For all $t < t_{Bmax}$, B's dominant strategy is to wait.

Step 4: Given firm B's behaviour, firm A must essentially choose between moving first, in which case it maximises its payoffs by introducing at t_{Amax} or moving second, in which case it will follow B's entry date of t_{Bmax}. In other words, A's best response to B's strategy is to move first at t_{Amax} if $\pi_A^l(t_{A\max}) \geq \pi_A^f(t_{B\max})$ and to let B introduce first at t_{Bmax} otherwise.

An abbreviated argument for the analogous symmetric ability case is the following:

Necessary conditions

If a strategy combination is a subgame perfect equilibrium for G^0, then one of the two following local strategy combinations must be part of it:

$$(s_A^t, s_B^t) = \begin{cases} (1,1) \text{ for } t=0,\ldots,t_{max}-1 \\ (0,1) \text{ for } t=t_{max} \end{cases} \quad \ldots\text{or}\ldots \quad \begin{cases} (1,1) \text{ for } t=0,\ldots t_{max}-1 \\ (1,0) \text{ for } t=t_{max} \end{cases}$$

In other words, no firm stops before t_{max}, at which point one of the two stops. The other continues.

At least one firm must stop its research no later than t_p since if firm B did not stop, firm A's best response would be to stop (and conversely) from the definition of t_p. Therefore, (1,1) for all $t \le t_p$ cannot be part of equilibrium local strategies for G^0. Furthermore, (0,0) at any $t \le t_p$ cannot be part of a subgame perfect equilibrium of G^0 since firms always prefer following to introducing at the same time. Thus, (1,0) or (0,1) must be played at some time $t \le t_p$. Define t^* as the smallest time, t, at which either of these strategies is played. Let us now show that $t^* = t_{max}$.

First, note that $t^* \ge t_{\max}$ since it is a dominant strategy for each firm not to stop before t_{max} from the definition of t_{max} as the date that maximises the payoff to either firm from stopping first. Assume that $t^* > t_{max}$. If (0,1) is played at t^*, then firm A does better by stopping at $t^* - 1$ than waiting. Similarly, if (1,0) is played at t^*, then firm B is better off moving at $t^* - 1$. Therefore, we must have $t^* = t_{max}$.

Sufficient Conditions:

The two following strategy combinations are subgame perfect equilibria of the game G^0:

$$(s_A^t, s_B^t) = \begin{cases} (1,1) \text{ for } t=0,\ldots,t_{max}-1 \\ (0,1) \text{ for } t=t_{max}, t_{max}+2, \ldots \\ (1,0) \text{ for } t=t_{max}+1, t_{max}+3,\ldots \end{cases}$$

and (iv)

$$(s_A^t, s_B^t) = \begin{cases} (1,1) \text{ for } t=0,\ldots,t_{max}-1 \\ (1,0) \text{ for } t=t_{max}, t_{max}+2, \ldots \\ (0,1) \text{ for } t=t_{max}+1, t_{max}+3,\ldots \end{cases}$$

The proof is almost identical to the proof of sufficient conditions for the pre-emptive equilibrium and so will not be repeated. (In other words, with the substitution of the subscript "max" for the subscript "p", we can repeat almost the same text.) Details are available from the authors upon request.

The parameter ranges for which Case I and Case II prevail were derived in lemma 3, above.

Proof of proposition 2: Comparison of socially optimal entry date and privately optimal entry date for follower: For $\frac{\theta}{r} \ge 2.55c$, the second mover, firm B, introduces at $t_B = t_A + \frac{1}{r} + \frac{c}{\theta}$ and appropriates the whole market (see lemma 1). A social planner would maximise $\frac{1}{r}(e^{-rt_B} - e^{-rt_A})SS^M + \frac{1}{r}e^{-rt_A}(\theta t_A - \frac{c}{2})$ so that she would choose $t_B^S = t_A + \frac{1}{r}$ if $\theta t_A \geq 2c$ and $t_B^S = t_A + \frac{\theta}{4}t_B^2 + \frac{c}{2\theta}$ if $\theta t_A < 2c$. Simple computations show in both cases that $t_B > t_B^S$.

For $\frac{\theta}{r} \in]1.804c, 2.55c[$, the second mover introduces at $t_B = t_A + \frac{2}{r} - \frac{3c}{\theta}$. Social surplus is maximised by t_B^s such that $t_B^{s^2} + [\frac{18c}{5\theta} - \frac{2}{r}]t_B^s + \frac{9c^2}{5\theta^2} - \frac{18c}{5r\theta} = 0$. Evaluated at $t_B = t_A + \frac{2}{r} - \frac{3c}{\theta}$, this first order condition is greater than zero so that $t_B^s > t_B$.

If the equilibrium is stand alone so that $\frac{\theta}{r} \in [1.5c, 1.804c]$, numerical simulations confirm that, given an initial date of introduction, t_A, the interval before the second product is introduced is also too short.

Proof of proposition 3: For large parameter range, comparison of socially optimal entry date and privately optimal entry date of leader

Define $z = \frac{rc}{\theta}$. For $\frac{\theta}{r} \geq 2.55c$, one gets $t_s^l = \frac{1}{r}[1 - e^{-1}e^{-z}] + \frac{c}{2\theta}(1 - 2e^{-1}e^{-z})]$ which is greater than $t_p = \frac{c}{\theta} + \frac{1}{r}(\frac{e^{-1}e^{-z}}{1 - e^{-1}e^{-z}})$ if and only if:

$$\frac{z}{2} + x(1 + z + (\frac{1}{1-x})) < 1 \text{ where } x = e^{-1}e^{-z} \qquad \text{(v)}$$

If we have $\frac{\theta}{r} \geq 2.55c$, this implies that $z \in [0.0.392]$. At z=0, we have x=0.368. Similarly, at z=0.392, we have x=0.249. Defining the left hand side of (v) as H, we can show that $\frac{dH}{dz} < 0$ over the range considered. Since (v) is satisfied at z=0, (v) must be satisfied for z>0 as well. Numerical simulations confirm that the entry date is too early compared to the social optimum for the stand-alone equilibrium as well, $\frac{\theta}{r} \in [1.5c, 1.804c]$. Numerical simulations show that, when $\theta_A = \theta_B = \theta$ and $2.19c < \frac{\theta}{r} \leq 2.55c$ or $1.5 < \frac{\theta}{r} \leq 1.804c$, the leader enters too early. This is not the case for the intermediate range $1.804c < \frac{\theta}{r} \leq 2.19c$. See the end of this appendix for the analytical results upon which these simulations were based.

Proof of proposition 4: Range for which minimum quality standard improves welfare

Proposition 3 showed that the pre-emption date occurs before the initial introduction time that would maximise welfare given that the second firm chooses its introduction date non-cooperatively. In other words, the first product is introduced too early. Suppose that we impose a binding minimum quality standard of $q \geq \theta t_s^l$ so that the leader must offer no less than the socially optimal quality. Lemma 1 has shown that the lag between first and second introductions is independent of the date of first entry. Hence, a minimum quality standard will ensure an initial introduction date at t_s^l without affecting the quality difference between the two products. The proposition follows immediately from this observation.

Proof of proposition 5: Novelty requirement can improve welfare

A novelty requirement would translate into a requirement that q_A-q_B > N for some minimum novelty requirement, N. This can only modify behaviour if N is binding so that N > $t_A^*(t_B) - t_B$. Note that, for any given initial introduction date, we have seen in proposition 2 that delaying entry of the follower decreases social welfare for $\frac{\theta}{r} \geq 2.55c$ and improves welfare for $\frac{\theta}{r} < 2.55c$ as long as the equilibrium is pre-emptive (which occurs for $\frac{\theta}{r} > 1.804c$). Second, for any initial introduction date, it is clear that a larger and binding novelty requirement must decrease the follower's discounted profit. Indeed, if a pre-emption equilibrium occurs (i.e., $\frac{\theta}{r} > 1.804c$), this must also have the effect of speeding up the initial introduction date since a pre-emption equilibrium occurs when the follower is indifferent between moving first or second.

We must combine these effects together to evaluate the net effect on welfare. For the range over which a stand alone equilibrium prevails, (i.e., for $\frac{\theta}{r} < 1.804c$), the date of initial introduction is independent of the delay chosen by the follower. Indeed, the stand alone equilibria occur at a corner solution where the leader decides just to serve the entire market during her period of monopoly. It is because the equilibrium occurs at such a corner that a -- small enough -- novelty requirement does not affect the date of initial introduction. The result in the text then follows immediately.

For an intermediate range where a pre-emption equilibrium occurs but where $\frac{\theta}{r} < 2.55c$, we know first that a pre-emptive equilibrium prevails. From the definition of this equilibrium, any reduction in the follower's profit due to a binding novelty requirement will shift back the pre-emption date, lowering the leader's profit as well. From proposition 2 that the effect on the follower's entry date – taken alone – has a positive welfare effect while the effect on the entry date of the leader need not improve welfare. Indeed, numerical simulations show that this only increases welfare for $\frac{\theta}{r} \in]1.804c, 2.19c[$, the range for which the leader enters while it decreases welfare above this range because entry occurs (socially) too early for $\frac{\theta}{r} \in]2.19c, 2.55c[$.

For $\frac{\theta}{r} \geq 2.55c$, and replacing the optimal waiting time of the follower by N, and setting $\pi^f = \pi^l$, one gets:

$$t_p = (N - \frac{c}{\theta})\frac{e^{-rN}}{1-e^{-rN}} + \frac{c}{\theta}.$$

Notice that $\frac{\partial t_p}{\partial N} < 0$, as $(1-e^{-rN}) < N - \frac{c}{\theta}$ for binding N (i.e. for $N \geq \frac{1}{r} + \frac{c}{\theta}$). Hence, a binding novelty requirement shifts up (i.e. to an earlier date) the date of entry in the pre-emption equilibrium. We know from proposition 3 that the pre-emption date without a novelty requirement is already earlier than the social optimum. Since, following this argument and proposition 2, over the range considered we have $N \geq t^f(N=0) > t_s^f$, which is the socially optimal following date and we also have from this argument and proposition 3 that $t_p(N \text{ binding}) \leq t_p(N=0) < t_s$, a binding N must decrease welfare.

Sketch of the Proofs of Propositions 6 and 7:

For $\theta_A < \theta_B$, so that firm B is the better researcher, assume that the following six rankings of introduction dates can occur:

1. $t_{pA} \leq t_{pB} < t_{A\max} < t_{B\max}$
2. $t_{pB} < t_{pA} \leq t_{A\max} < t_{B\max}$
3. $t_{pB} < t_{A\max} < t_{pA} \leq t_{B\max}$
4. $t_{A\max} < t_{pB} < t_{pA} \leq t_{B\max}$
5. $t_{A\max} < t_{pB} \leq t_{B\max} < t_{pA}$
6. $t_{A\max} < t_{B\max} < t_{pB} < t_{pA}$

Indeed, numerical computations indicate that these are the only rankings that do, in fact, occur. Hence, treating only these cases should not be viewed as restrictive at all.

The argument for the stand alone equilibrium (ranking 6) was presented as part of proposition 1. Now, consider briefly the case of a pre-emption equilibrium, so that either the first or the second ranking, above, prevails. In this case, it could be the case that firm A introduces first at time t_{pB} (if ranking 1 prevails) or that firm B introduces first at time t_{pA} (if ranking two prevails). The proof for the first ranking is presented as part of the proof of proposition 1. In other words, recall that we proved that case for an assumption of asymmetric abilities, stating that the symmetric case was analogous. The proof for the second ranking is analogous to the case of the first ranking and so it, too, is omitted for brevity.

Given this, proceed to the application of a minimum quality standard. We can find cases for both types of equilibria where the minimum quality standard changes the order of entry.

Consider the stand alone case first, that of ranking 6 and recall that in this case the unique subgame perfect equilibrium outcome is that firm A moves first at t_{Amax} if and only if $\pi_A^l(t_{A\max}) \geq \pi_A^f(t_{B\max})$ while firm B moves first at t_{Bmax} if and only if $\pi_A^l(t_{A\max}) < \pi_A^f(t_{B\max})$. A minimum quality standard can change the order of moves in this case. Consider the case where firm A introduces first in equilibrium. Define t' such that $\pi_A^l(t') = \pi_A^f(t_{B\max})$. Any minimum quality standard in excess of $\theta_A t'$ but no greater than $\theta_B t_{B\max}$ would make firm A's discounted profits as a leader at time $\frac{q_{\min}}{\theta_A}$ lower than its profits as a follower, changing the equilibrium outcome to one where firm B introduces first. For minimum quality requirements larger than $\theta_B t_{B\max}$, firm B wants to introduce first as soon as it can meet the standard. Since $\theta_B > \theta_A$, firm A cannot meet the quality requirement as early as firm B and cannot, therefore, prevent firm B from introducing first at $\frac{q_{\min}}{\theta_B}$. Hence, a strengthening of the minimum quality standard can induce a change in leadership from the less to the more skilled researcher in this case. Moreover, as the stand alone entry date is smaller than the social optimum, the optimal minimum quality requirement is always large enough to reverse the order in which the two firms introduce their products in this case.

In an equilibrium for ranking 1 (where a pre-emptive equilibrium prevails), recall that the unique subgame perfect equilibrium outcome is that firm A introduces first at date t_{pB}. If the minimum quality standard, q_{min}, is binding, we must, then, have $q_{min} > \theta_A t_{pB}$, so that firm A cannot introduce until after t_{pB}. After t_{pB}, firm B prefers to move first. Since firm B will always be able to satisfy the minimum quality requirement before firm A (because we have assumed that $\theta_A < \theta_B$) , it will indeed move first.

Since the proofs for cases 3, 4, and 5 of the rankings of entry times, above, are almost identical, we will only sketch the proof for ranking 4: $t_{A\max} < t_{pB} < t_{pA} \leq t_{B\max}$. As before, firm B is assumed to be the better researcher. In this case, the game G^0 has a unique subgame perfect equilibrium where firm A introduces first at t_{Amax} if and only if the date t_c, defined below, is no greater than t_{pB} and firm B introduces first at t_c-1 if and only if $t_c > t_{pB}$. The argument for this equilibrium outcome is outlined in the next seven steps:

Step 1: There cannot exist a subgame perfect Nash equilibrium where both firms introduce at the same time. This follows directly from lemma 4, which shows that the low-θ firm would always prefer to follow rather than to introduce at the same time as its rival.

Step 2: If there is a subgame perfect Nash equilibrium where firm A stops first then, in this equilibrium firm A stops at t_{Amax}. First, it is a dominant strategy for A not to stop before t_{Amax}. Second, $\pi_A^l(t) < \pi_A^l(t_{A\max})$ for all $t > t_{Amax}$ so that A moving first after t_{Amax} cannot be a subgame perfect Nash equilibrium. These arguments follow from our definition of t_{Amax}.

Step 3: If there is a subgame perfect Nash equilibrium where firm B stops first then, in this equilibrium, firm B must stop no earlier than t_{pB} and no later than $t_c - 1$ where t_c is defined by the following backward induction argument. If the game reaches t_{pA}, A stops (first). Given this, and step 1, there are two subgame perfect equilibria at $t_{pA} - 1$: (0,1) and (1,0). Let us select the equilibrium (1,0), i.e. B stops at $t_{pA} - 1$. Indeed, while one possible justification for this selection is that (1,0) Pareto dominates (0,1), selecting (0,1) would not modify the argument substantially. Given that B stops at $t_{pA} - 1$, with a fine enough grid both A and B decide to wait at all t such that $t_{pA} - 1 > t > t_1$, where t_1 is defined as the largest t in this range such that $\pi_A^l(t) > \pi_A^f(t_{pA} - 1)$. Notice that this follows from the ranking we have assumed of stopping dates and our initial definitions of these dates. Given this, A would stop at t_1. Thus, B would stop at t_l -1 (again, given our ranking of entry dates). As a result, both A and B decide to wait for all t such that $t_1-1>t>t_2$ where t_2 is defined as the largest t such that $\pi_A^l(t) > \pi_A^f(t_1 - 1)$. This argument can be repeated to define t_3, t_4, …t_i…. Define t_c as the t_i with the smallest index, i (which will be the largest in the sequence of dates) such that $\pi_A^f(t_c) > \pi_A^l(t_{A\max})$. In other words, A will stop at t_c if this point is reached without introduction, so that an equilibrium with B introducing first cannot occur later than t_c -1. Such an equilibrium cannot occur before t_{pB} either since waiting is B's dominant strategy for all $t<t_{pB}$.

Step 4: From steps 2 and 3, it follows that if $t_c \le t_{pB}$ then the only possible subgame perfect Nash equilibrium outcome has A stopping first at t_{Amax}. More precisely, A would stop at t_c but, because $t_{pB} > t_c$, B does not want to stop at t_c-1 so that, were the game to proceed that far, A would introduce first at t_c, in which case A prefers to move first at t_{Amax}.

Step 5: If $t_c>t_{pB}$ then the only possible subgame perfect Nash equilibrium outcome is for B to stop first at $t_c - 1$. In other words, A would stop at t_c so that B stops at t_c -1 since B is willing to pre-empt over this range. However, by the definition of t_c, $\pi_A^f(t_c - 1) > \pi_A^l(t_{A\max})$ (for our fine grid) so that A waits. Given this, B also waits at $t<t_c$-1 so that B stopping first at t_c -1 is the only possible subgame perfect outcome.

Step 6: If $t_c \le t_{pB}$, the candidate subgame perfect equilibrium outcome described in step 4 can be supported by the following strategy combination:

$$(s_A^t, s_B^t) = \begin{cases} (1,1) \text{ for } t=0,\ldots,t_{Amax}-1 \\ (0,1) \text{ for } t=t_{Amax}, t, \ldots, t_{pA}+1, t_{pA}+2, \ldots, t_{Bmax}-1, \ldots \\ (1,0) \text{ for all } t \ge t_{B\max} \end{cases}$$

Step 7: If $t_c>t_{pB}$, the candidate subgame perfect equilibrium outcome described in step 5 can be supported by the following strategy combination:

(1,1) for $t=0,\ldots,t_c-2$, t_c+1, t_c+2, $t_{c-1}-2$, $t_{c-1}+1$, $t_{c-1}+2$,…t_1-2

$(s_A^t, s_B^t) =$ (0,1) for $t=t_c,\ldots,t_1, t_{pA}, t_{pA}+1, t_{pA}+2\ldots$
(1,0) for all $t_c-1, t_{c-1}-1,\ldots t_1-1, t_{pA}-1$

This concludes the derivation of the equilibrium. Now, we move on to consideration of the minimum quality standard. The equilibrium we have derived is one where the more efficient firm, firm B, moves first ($t_c \geq t_{pB}$). The unconstrained equilibrium is such that firm B moves first at $t_c-1 \geq t_{pB}$. As such, any minimum quality standard $q_{min} \leq \theta_A t_c$ is ineffective since it does not prevent firm A from credibly threatening to introduce first at t_c. For $\theta_A t_c < q_{\min} \leq \theta_A t_{c-1}$, firm A can only credibly threaten to stop at t_{c-1} so that firm B introduces first at $t_{c-1}-1$. Following the same reasoning, one can see that greater values of q_{min} induce later dates of first introduction by B in a stepwise fashion. Now let $\theta_A t_{pA} < q_{\min} \geq \theta_A t_{B\max}$. Firm A cannot introduce before t_{pA} (since the minimum quality standard does not allow it). This induces firm B to move first at $\frac{q_{\min}}{\theta_A} - 1$. If $q_{\min} > \theta_A t_{B\max}$ then firm A cannot introduce before t_{Bmax} (since the minimum quality standard does not allow it). Hence, we have a stand alone equilibrium where firm A introduces first at t_{Bmax}.

On the other hand, we have that when $t_c < t_{pB}$, firm A introduces first at t_{Amax} in the unconstrained equilibrium. Define t_i^* as the largest t_i which is still smaller than t_{pB} and t_{i-1}^* as the smallest t_i which is larger than t_{pB}. The earliest date at which firm B will want to introduce first is $t_{i-1}^* - 1$. Therefore, any minimum quality requirement such that $\theta_A t_{A\max} < q_{\min} \leq \theta_A t_i^*$ just pushes back the date of firm A's introduction to $\frac{q_{\min}}{\theta_A}$. For $\theta_A t_i^* < q_{\min} \leq \theta_A t_{i-1}^*$, however, firm A prefers to let firm B introduce first at t_{i-1}^* and the minimum quality requirement reverses the order of introduction. For even larger minimum quality requirements, the analysis is analogous to that of the previous paragraph.

Sketch of analytical results used to establish results from numerical simulations

To perform the numerical computations we must determine t_{imax}, t_p and t_s^l for $\frac{\theta}{r} \in]1.5c, 2c]$.

1. t_{imax}

Assume first that $t_{i\max} > \frac{2c}{\theta}$ so that the whole market is served during the initial monopoly period. Under this assumption we have:

$$t_{i\max} = \frac{1}{r} + \frac{c}{\theta} - 2\frac{c}{\theta}\frac{x}{1-x}\left(1 - \frac{\theta}{3rc}\right)^2$$

Where $x = e^{-1}e^{\frac{-rc}{\theta}}$. Numerical computations show that this is indeed greater than $\frac{2c}{\theta}$ for $\frac{\theta}{r} \geq 1.804c$. Let us now assume that $t_{i\max} < \frac{2c}{\theta}$. Under this assumption, it follows that:

$$t_{i\max} = \frac{1}{r}(1 + [1 - \frac{8e^{-2}e^{\frac{3rc}{\theta}}}{9(1 - e^{-2}e^{\frac{3rc}{\theta}})}]^{\frac{1}{2}})$$

Which numerical computations show to be larger than $\frac{2c}{\theta}$. This is a contradiction. Hence, it follows that $t_{i\max} = \frac{2c}{\theta}$ must hold for the range for which stand alone equilibria prevail. Numerical computation show that this range is $\frac{\theta}{r} \in]1.5c, 1.804c[$.

2. t_p

Assuming that $t_p \geq \frac{2c}{\theta}$ we get

$$t_p = \frac{c}{\theta} + \frac{2c}{\theta}\frac{Y}{1-Y}(\frac{2\theta}{3rc} - 1)$$

where $Y = e^{-2}e^{\frac{3rc}{\theta}}$. Computations show t_p to be always greater than $\frac{2c}{\theta}$ for all $\frac{\theta}{r} > 1.5c$.

3. t_s^l

Assuming that $t_s^l \geq \frac{2c}{\theta}$, one gets

$$t_s^l = \frac{1}{r} + \frac{c}{2\theta} + \frac{Y}{3r}(2 - \frac{5\theta}{3cr}) \text{ where } Y = e^{-2}e^{\frac{3rc}{\theta}}$$

Which is indeed greater than $\frac{2c}{\theta}$ if and only if

$$\frac{\theta}{r} < \frac{9}{5}c(\frac{2}{3} + \frac{1}{Y})$$

which numerical computations show to be satisfied for all $\frac{\theta}{r} > 1.5c$.

4. Comparison of the different stopping times

Based on steps 1, 2 and 3, above, for $\frac{\theta}{r} < 1.804c$, we know that $t_p > \frac{2c}{\theta} = t_{imax}$ so that the equilibrium must be "stand alone". Since $t_s^l > \frac{2c}{\theta} = t_{i\max}$, a minimum quality standard of θt_s^l is called for in this range. For $1.804c \le \frac{\theta}{r} \le 2c$, $t_p < t_{imax}$ for $\frac{\theta}{r} > 1.804c$ so that we have a pre-emptive equilibrium over this range if and only if $t_p < t_{imax}$:

$$t_p = \frac{c}{\theta} + \frac{2c}{\theta}\frac{Y}{1-Y}\left(\frac{2\theta}{3rc} - 1\right) < t_{imax}$$

Numerical computations show that this holds, indeed, for this range. Hence, we have a pre-emption equilibrium over this range. Furthermore, computations show that the pre-emptive equilibrium occurs earlier than t_s^1 -- so that a minimum quality standard is desirable -- if and only if $\frac{\theta}{r} \le 2.19c$. This is clearly the case for the parameter range we are considering.

Brief description of numerical simulations for footnotes

General methodology: The simulations were run by using MathCad 4.0 for Windows. The general methodology of these programmes is as follows:

1. Iterate on the introduction date of the leader.
2. The optimal behaviour of the follower is determined by our lemma 1, above, or by a novelty requirement if it is binding.
3. The profits of the leader and follower as well as social surplus are obtained, both with A as leader and with B as leader.
4. The equilibrium is determined by inspection of these four elements. In other words, one determines which of the six rankings we listed at the beginning of the proof for propositions 6 and 7 actually prevails. Since the programme is run again for each combination of parameters, the size of the iteration grid can be adjusted to each case in order to remove any possible ambiguity as to which ranking occurs.
5. Simulations were performed for a large number of combinations of $\frac{\theta}{rc}$ (and for an even larger number when θ_A and θ_B were not equal). It is important to notice that two special problems arise in finding the equilibrium through simulations when rankings 3, 4 or 5 prevail. First, the precise value of t_c and

its position relative to t_{pB} depend on the grid used. In other words, a change in the size of the grid can affect the equilibrium outcome. To minimise the effect, simulations for these cases were run on a grid up to 10,000 times finer than simulations used for rankings 1, 2 and 6. The second problem is the multiplicity of equilibria resulting from the existence of two pure strategy equilibria at t_{pA} -1, t_1-1, …. In the text, we derived the subgame perfect equilibrium outcome of G^0 when the Pareto superior equilibrium is believed to arise at each of these points. Other selection rules would not affect the nature of the argument presented in the text but they could, for a given grid, lead to rather different outcomes. Fortunately, the use of an extremely fine grid in out simulations also helps alleviate this problem because all these equilibria converge to the same outcome in the continuous limit.

Note: We do not show in proposition 4 (analytically) that stand alone equilibrium is less than social optimum. We only show this for theta > 2.55rc. Lower range follows from numerical simulations only. We'd have to assume step 2's condition.

Note: Numerical simulations allow us to describe the regions for which minimum quality standards improve welfare – or not. Indeed, we find that there is an intermediate region $(1.804c < \frac{\theta}{r} < 2.19c)$ where quality standards cannot improve welfare, while a welfare-improving standard can be found for lower values of research ability.

Economics
The Open-Access, Open-Assessment E-Journal

Please note:

You are most sincerely encouraged to participate in the open assessment of this discussion paper. You can do so by posting your comments.

Please go to:

http://www.economics-ejournal.org/economics/discussionpapers/2009-33

The Editor

© Author(s) 2009. Licensed under a Creative Commons License - Attribution-NonCommercial 2.0 Germany