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

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Abstract We examine the timing and quality of product introduction in an R&D stopping game, where we allow for horizontal and vertical differentiation in the product market. We observe that discontinuous changes in introduction dates can occur as firms' abilities as researchers change. Further, when the research abilities of the firms differ, either the high ability firm or the low ability firm may be the first mover. The underlying research abilities of the firms determine the social optimality of the entry patterns we observe. Minimum quality standards and novelty requirements can play a role in correcting these suboptimal patterns of entry. While minimum quality standards increase welfare for a large range of research abilities, we find that increasing the novelty requirement does not necessarily increase either the profits or, consequently, the research investment incentives of the initial innovator, contrary to much of the cumulative innovation literature. Indeed, as the effect of policy interventions differs significantly across industries where quality improvement is steep and those where it is flat, targeted policies towards specific industries as are often observed in minimum quality standards are generally preferable to more broad-based policies.

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1 Introduction

This paper studies the effect of two policy instruments, minimum quality standards and novelty requirements of patents, on the timing of introduction of new products. Both these instruments are pervasive in industries where new products are based on advanced technologies. Setting and enforcing minimum quality standards for high technology products forms a large part of the work of institutions such as the National Institute for Standards and Technology, and the Federal Drug Administration in the United States. Indeed, bodies such as the British Standards Institute have literally hundreds of quality standards they apply across the gamut of industries from aerospace to information technology.[1] Minimum novelty requirements for patentability are present in most patent systems, specifying a minimum "inventive step"—or its equivalent—as a prerequisite for legal protection of new technology.

Both minimum quality standards and minimum inventive step are costly instruments to create and maintain, with budgets running into the hundreds of millions yearly.[2] As a result, it is important to understand whether and how they generate benefits. A variety of rationales for each instrument have been proposed in the literature. Minimum quality standards have been justified as mitigating information asymmetries that could hinder market operation (Leland, 1979 and Shapiro, 1983), and restricting the lower range of qualities offered by a monopolist attempting to capture surplus from a market (Mussa and Rosen, 1978). In more recent support for minimum quality standards, Ronnen (1991) shows that, in a Shaked and Sutton (1987) framework with multiple producers and endogenous

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[1] See National Institute for Science and Technology website, www.nist.gov for exhaustive discussion of standards-setting for a variety of fields in the US. These quality standards often refer to safety and some level of performance (equivalent to efficacy in drugs) for the intended purpose, but may also involve minimal environmental harm or other measures of "quality". We do not focus on the precise meaning of "quality" for consumers but instead simply assume that this characteristic is valued by them in some way.

[2] To put some rough numbers on this, the 2004 budget for the National Institute for Science and Technology was approximately $500Mm, including all its activities; the portion of the United States Patent and Trademark Office budget allocated to optimising patent quality and timeliness was projected at $2Mm for fiscal year 2009. See www.nist.gov and www.uspto.gov.

(costly) quality, a minimum quality standard 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 seller to raise its own quality in an effort to alleviate price competition.[3] Regulation of the inventive step as a "patentability requirement" affects the incentive to invent because it can modify the bargaining positions of different firms that participate in cumulative innovation (Scotchmer, 1996) and so can affect the division of surplus between early and later innovators. It can also modify the effective length of protection of a patent (O'Donoghue, Scotchmer and Thisse, 1998) when the inventive step is defined as a quality margin that must be maintained between innovations in order to obtain a separately patentable innovation (and one that does not infringe earlier patents). O'Donoghue (1998) points out that requiring a larger quality "step" for patentability can result in research only targeting larger steps. If these larger steps also take longer to accomplish, a more stringent patentability requirement comes hand in hand with a longer incumbency period and so increases innovation incentives.

We study a one-shot "stopping time" framework where firms strategically choose their timing of entry and the quality of the product they choose to introduce. The payoffs of our firms depend on both the quality level of the product introduced and the difference in the qualities of the products. Such games have been studied by a series of authors, including Dutta, Lach and Rustichini (1995) and more recently Hoppe and Lehmann-Grube (2005). Our game shares with these earlier papers the feature that 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

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[3] 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). Note that quality standards have also been studied in the international context by Boom (1995), Herguera and Lutz (1998) and Motta and Thisse (1993) and empirically by Gruber and Verboven (2001). For recent policy discussion, see Manski (2009).

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.[4] 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, whether firms “race” is endogenous: while the firms race—and so dissipate profits—when they are both highly skilled, less-skilled firms tend to settle into an equilibrium without pre-emption.

We introduce to these models both the possibility that the firms may differ in their research abilities, which we define as the rate at which a researcher can improve product quality of a prototype, the possibility that minimum quality standards may prevent introduction of a product that is of too low a quality, or a patentability requirement may effectively prevent entry with an improvement that is too small a quality increment over what is already on the market.

When we allow firms to differ in their research abilities, we find that there is no necessary correlation between research skill and either quality of the final product or the order of entry. This result, which is broadly similar to that of Riordan (1992)’s study of the timing of entry, 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 latter authors do not allow the 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: costs, waiting, and quality are all tied together in our model. While Argenziano and Dengler’s (2008) study of the order of entry and firm characteristics shares our intuition, their framework exogenously assigns profit flows to the entrants whereas we derive profits endogenously. In both our paper and theirs, a “more skilled” firm has a stronger incentive to enter because it tends to have higher profit potential. At the same time

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

it must balance this incentive to enter early against the fact that a less skilled researcher may still enter in the future with a higher quality product that will reduce the first mover's profits. If the low 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.

Without policy intervention, we find that the leader may enter socially 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 skill levels. When both 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. In contrast, when both researchers' skill is very low, 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. A minimum quality standard, which effectively prevents entry into the market before a given date, may or may not improve welfare, depending on which skill range prevails: 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. In contrast to earlier work, then, minimum quality standards may not improve welfare when we consider their feedback effect on the timing of entry.

When the two researchers are of differing ability the minimum quality standard has additional effects in that we observe 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 the minimum quality standard can also affect the delay between first and second product introductions in this case. More precisely, when the more able firm moves first, a minimum quality standard can 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, as it affects the order as well as the timing of entry.

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. In the context of our model of both vertical and horizontal differentiation, consider the example of two products that are currently produced based on a large number of patents, and are currently manufactured and sold under different brand names. The existing branding and design features of the products are taken as "exogenous" horizontal differentiation in our model. The firms now contemplate introducing a new technological feature that will increase the quality of their respective offerings. The impact of a novelty requirement on this new feature is what we study. 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, echoing the O'Donoghue (1998) interpretation. We find that, like a minimum quality standard, the novelty requirement improves welfare when both firms are of high or low research abilities, with no necessary improvement over an intermediate range. Counter-intuitively, and in contrast to much of the literature on the effects of novelty requirements, 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, however.[5] 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.

[5] Papers supporting weak patent protection have ranged from those that assume costly or slow adoption which generates rents in the place of patents, those that allow other intellectual property tools such as trade secrets to substitute for patents, and those that generate excess research or a monopoly distortion when protection is very strong. See Rockett (2010) for a survey. In contrast to some recent papers that study patent strength in a quality ladder model with exogenous "roles", we focus on endogenous order of entry rather than the structure of patent protection. Again, see Rockett (2010) for a survey of these papers and other literature on the analysis of patent protection.

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 the 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 i at time t is $q_i(t) = \theta_i t$, where θ_i measures firm i's "skill" in research. Notice that we assume that firms cannot—completely— resolve the problem of waiting by "throwing money" at the research problem. One interpretation of this would be that we focus on research which is still at the stage where blind alleys must be defined and investigated, research questions must be honed down, or where clinical trials are necessary, rather than at the late stage where only final development and commercialisation must occur.

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".[6] However, this assumption is also justified in

[6] Dutta et al. (1995) 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

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 by 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 could be thought of to reflect Rosenberg's (1982) 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:

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

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. Notice that, since every consumer has the same marginal valuation of product quality, there is a vertical dimension but there is no room for vertical differentiation strategies.

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

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

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

incumbent may very well enter earlier because the entrant has superior ability to commit not to enter early.

depending on whether the market is partially or completely served. When both firms offer a product on the market, given the firms' quality, firms set price non-cooperatively to maximise profits, resulting in profits for firm i of:

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

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

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

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 (non-cooperatively) chooses 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 that has not yet introduced its product must decide whether to introduce now or to proceed with further development.

We consider first the situation where both firms have 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. Given that the other firm has already introduced at time t_j, the follower, firm i chooses its own date of introduction t_i to maximise the discounted value of its profits. The profit function of the follower takes one of two possible forms depending on how long it waits before introducing its own product. If the follower moves fairly quickly after the leader, then the quality difference between the two products is such that both firms have positive sales. In that case, the profit function of the follower can be written as:

$$\pi_i^F(t_i,t_j)=\int_{t_i}^{\infty}\frac{c}{2}[1+\frac{\theta}{3c}(t_i-t_j)]^2 e^{-rt}dt \text{ if } \theta(t_i-t_j)\leq 3c$$

On the other hand, the follower can also decide to wait long enough that the quality advantage of its product ensures that it captures the whole market. In that case, the profit function of the follower is:

$$\pi_i^F(t_i,t_j)=\int_{t_i}^{\infty}[\theta(t_i-t_j)-c]e^{-rt}dt \text{ if } \theta(t_i-t_j)\geq 3c$$

Maximising these profit functions, keeping track of the ranges over which they apply, we can describe the optimal behaviour of the follower as follows.

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 when firms' research abilities are symmetric is given as:

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

$t_i(t_j) = t_j + (2/r) - 3c/\theta$ *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, ensuring that the two firms never find it optimal to introduce at the same date. 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.[7] 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.

The payoffs of this "stopping" game are illustrated in Figures 1a and 1b 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. This profit function potentially takes four possible forms, depending on whether the leader waits long enough that it finds it optimal to serve the whole market during its period of monopoly and on whether the follower goes for an incremental or a drastic innovation. However, given the parameter ranges over which each market configuration applies, only three cases need to be considered. Hence we have:

$$\pi_j^L(t_i,t_j) = \int_{t_j}^{t_i(t_j)} \frac{\theta t_j^2}{4c} e^{-rt} dt + \frac{c}{2} \int_{t_i(t_j)}^{\infty} [1+\frac{\theta}{3c}(t_i(t_j)-t_j)]^2 e^{-rt} dt$$

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[7] The profit function has a kink at the point of transition from incremental to drastic innovation, hence generating discrete behaviour at this point.

when the market is incompletely served by the monopolist and then shared with the follower. We have

$$\pi_j^L(t_i,t_j) = \int_{t_j}^{t_i(t_j)} [\theta t_j - c]e^{-rt}dt + \frac{c}{2}\int_{t_i(t_j)}^{\infty} [1+\frac{\theta}{3c}(t_i(t_j)-t_j)]^2 e^{-rt}dt$$

when the monopolist serves the whole market and then shares the market with the follower. Finally,

$$\pi_j^L(t_i,t_j) = \int_{t_j}^{t_i(t_j)} [\theta t_j - c]e^{-rt}dt$$

when the monopolist serves the whole market but is then excluded from the market by the follower's drastic innovation. In these three expressions, $t_i(t_j)$ represents the optimal time of introduction of the follower as specified in Lemma 1. The determination of the date t_s that maximises the profit of the leader, given the optimal further delay chosen by the follower, involves maximising a profit function made up of each of the three expressions above over the range for which they apply. The corresponding computations, and the parameter ranges over which each profit function applies are found in the appendix.

Depending on the parameter range, two types of equilibria emerge.[8] 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. This occurs 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 1a.

[8] We focus on pure strategy equilibria only in this analysis.

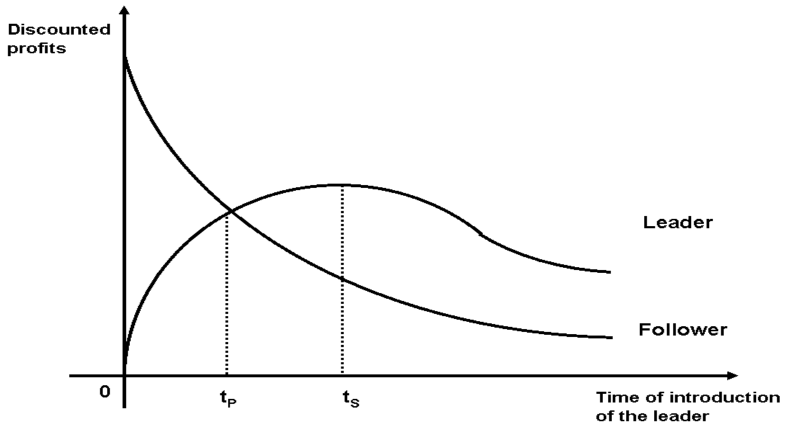

Figure 1a: Pre-emption Equilibrium

Following Dutta et al. (1995), we call this a "pre-emption" equilibrium. Lemma 2 derives the formal expressions for the pre-emption times:

Lemma 2: For moderate research ability, 1.5c < $\frac{\theta}{r}$<2.55c, we have a pre-emption time $t_p = \frac{c}{\theta} + \frac{2c}{\theta}\frac{Y}{1-Y}\left[\frac{2\theta}{3rc} - 1\right]$, for Y = $e^{-2}e^{\frac{3rc}{\theta}}$. For "high" research ability $\frac{\theta}{r} \geq$ 2.55c, we have $t_p = \frac{c}{\theta} + \frac{1}{r}\left[\frac{e^{\frac{-rc}{\theta}-1}}{1-e^{\frac{-rc}{\theta}-1}}\right]$.

Proof: See appendix.

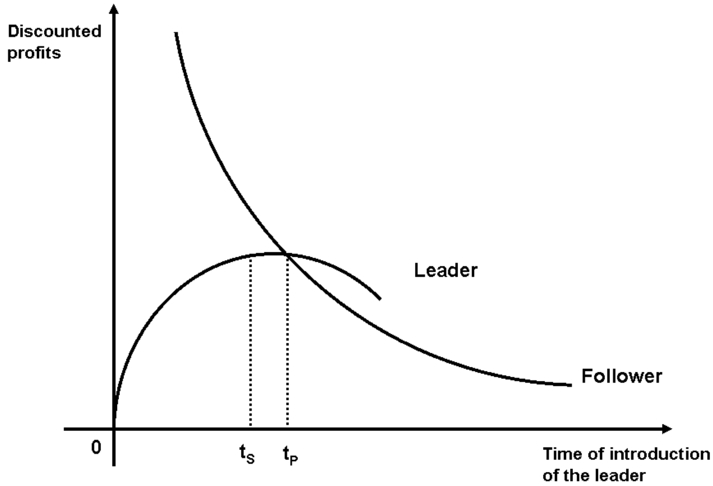

Figure 1b: Stand-alone Equilibrium

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 1b, 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".[9] In such an equilibrium, the follower makes higher profits than the leader. Completely describing the stand alone behaviour of the leader, we have:

Lemma 3: For "moderate" research ability $1.5c < \frac{\theta}{r} < 2.55c$, we have a stand-alone entry time $t_{j\max} = \frac{1}{r} + \frac{c}{\theta} - 2(\frac{c}{\theta})Y(1 - \frac{\theta}{3rc})^2 /(1-Y)$, where Y = $e^{-2}e^{\frac{3rc}{\theta}}$, and for "high" research ability $\frac{\theta}{r} \geq 2.55c$ we have $t_{j\max} = \frac{1}{r} + \frac{c}{\theta}$.

Proof: See appendix.

Using these entry times for the appropriate ranges, we obtain the following characterisation of the equilibria of this game:

Proposition 1: In the symmetric ability case, if the research abilities of the two firms are limited (i.e., $1.5c \leq \frac{\theta}{r} < \underline{\theta}$ < 2.55c), then there are two stand-alone subgame perfect equilibria in pure strategies where one firm introduces at time $t_{j\max} = \frac{1}{r} + \frac{c}{\theta} - \frac{2c}{\theta}\frac{Y}{1-Y}\left[1 - \frac{\theta}{3rc}\right]$, where Y = $e^{-2}e^{\frac{3rc}{\theta}}$, and the other firm introduces after the additional period defined in Lemma 1. For higher research abilities (2.55c > $\frac{\theta}{r}$ ≥ $\underline{\theta}$) there are two pre-emptive subgame perfect equilibrium outcomes, where one firm moves first at $t_p = \frac{c}{\theta} + \frac{2c}{\theta}\frac{Y}{1-Y}\left[1 - \frac{2\theta}{3rc}\right]$ and the other firm introduces after the additional period defined in Lemma 1. In each case, the two equilibria differ only in the identity of the firm that moves first.

Proof: See appendix.[10]

Indeed, numerical computations allow us to pin down a value of $\underline{\theta}$:[11]

Property 1: The two equilibrium outcomes are preemptive for 2.55c > $\frac{\theta}{r} \geq 1.804c = \underline{\theta}$, while they are stand-alone for 1.5c<$\frac{\theta}{r} < 1.804c = \underline{\theta}$.

Note that, in the propositions that follow, a general value $\underline{\theta}$ will be used but the properties will refer to the value of $\underline{\theta}$ derived in this property.

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[9] Dutta et al. (1995) label this a "maturation equilibrium".

[10] For this, and Propositions 6 and 7, a shortened version of the proofs is presented here. Please see the discussion paper version for a more complete presentation.

[11] Throughout the paper, we will use the term "property" for results that are at least partially based on numerical simulations. All other results are obtained analytically.

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:

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

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

and the entire market is served if and only if $q_A \geq 2c$.

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

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

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

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

Total discounted social surplus is given by:

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

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 (ie, would not be first-best). 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, and that the equilibrium is preemptive ($\frac{\theta}{r} \geq \underline{\theta}$) the interval before the second product is introduced can be either socially too short (for $\underline{\theta} \leq \frac{\theta}{r} < 2.55c$) or socially too long (for $\frac{\theta}{r} \geq 2.55c$).
Proof: See appendix.

Indeed, when the equilibrium is stand-alone, the interval before the second product is introduced is socially too short:

Property 2: For $1.5c < \frac{\theta}{r} < \underline{\theta}$, we have: $t_B < t_B^s$.

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[12] 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 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

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

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.[13] 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. 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 slowly.[14]

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.

Proposition 3: Assume that $\theta_A = \theta_B = \theta$. Given the second mover's optimal reaction, the initial date of introduction, t_A, will be too early compared to the social optimum if the speed of learning is large enough that the second mover enters with a drastic innovation, (i.e. $\frac{\theta}{r} > 2.55c$). For moderate research abilities, $1.5c < \frac{\theta}{r} \leq 2.55c$, the first product may be introduced too early or too late.

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13 In other words, $\pi_B^D - 0 \leq SS^D(t_A, t_B) - SS^M(t_B)$.

14 Other models, cited in our introduction, of cumulative innovation have not exhibited this feature because of restrictions on the nature of competition, 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. (although quantity effects are limited because the market size is fixed and consumers have unit demands).

Proof: See appendix.

To be more specific about the ranges over which behaviour occurs in the lower range, we compute the following:

Property 3: When $1.5c < \frac{\theta}{r} \leq \underline{\theta},$ the equilibrium is stand alone and the leader enters too early compared to the social optimum; when $\underline{\theta} < \frac{\theta}{r} \leq \overline{\theta} = 2.19c$ the equilibrium is pre-emptive and the leader enters too late compared to the social optimum; when 2.19c $= \overline{\theta} < \frac{\theta}{r} \leq 2.55c,$ the equilibrium is preemptive and the leader enters too early compared to the social optimum.

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 since the quality improves from leader to follower. 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 the date of 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 imposes a minimum absolute quality level that can be marketed. For example, the FDA does not allow commercialisation of drugs that fail to demonstrate via clinical trials a minimum threshold of safety and efficacy in their claimed use. This standard forces the first entrant (only) 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. Indeed, we already know that, over the range where stand alone equilibria prevail, the first product is introduced too 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 ($1.5c < \frac{\theta}{r} \leq \underline{\theta}$) or when they are large enough that the follower would enter with a drastic innovation

($\frac{\theta}{r} > 2.55c$). For intermediate values of research ability, the result depends the level of research ability: for ranges over which the leader enters too early, it improves welfare; for ranges over which the leader enters too late, it cannot improve welfare.

Proof: See appendix.

More specifically, we have:

Property 4: In the range $\underline{\theta} < \frac{\theta}{r} < \overline{\theta}$, the minimum quality standard cannot be used to improve welfare, while for $\overline{\theta} < \frac{\theta}{r} < 2.55c$, the minimum quality standard can improve welfare.

Combining this with our previous results, there is a relatively small intermediate range for which minimum quality standards cannot improve welfare in the pre-emption equilibrium. For low or high research abilities, and for ranges over which stand alone equilibria occur, they do.

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 another (patented) product to be allowed to exploit its own product commercially. The effect of a novelty requirement contrasts to the minimum quality standard, which prevents introduction of any product below some minimum absolute quality threshold even in the absence of any other product in the market. In the US, drugs that are patented are subject to standard novelty requirements on patentability that are administered and applied by the patent office separate from any quality standards imposed by the Federal Drug Administration (FDA).

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: 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 quite distinct conclusions from existing work.

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, in contrast, we know that the second product is introduced too quickly so that a novelty requirement can be used to increase welfare. Hence, we cannot make a blanket statement as to whether "strong" or "weak" patents are good either for firms or for welfare in this model, as it depends on the speed of evolution of the industry to which we apply it.

The effects that we have just described 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 any quality improvements can be enjoyed over a longer monopoly phase. Since initial entry occurs too early over this range, this effect improves welfare. It also ensures that—as in much of 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 decreases 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,[15] a binding novelty requirement ends up decreasing the profits of both the follower and the initial inventor. Putting these effects together gives us the results presented in Proposition 5.

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

For an intermediate range, there are two effects of the novelty requirement—speeding up the initial date of entry and slowing down the second date of entry—so that the final effect on welfare is ambiguous. We calculate the net effect in Property 5:

Property 5: For $\overline{\theta} \leq \frac{\theta}{r} < 2.55c$, a binding novelty requirement decreases welfare, while for $\underline{\theta} < \frac{\theta}{r} < \overline{\theta}$ a binding novelty requirement increases welfare.

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15 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.

The last part of Proposition 5 implies, perhaps counter-intuitively, that for the range over which pre-emptive equilibria arise, a binding socially optimal novelty requirement decreases profits, and hence R&D investment incentives 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 can lower the "opportunity cost" of being a follower and so allow 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.[16] Another interesting feature of this analysis is that it indicates that welfare can move quite discontinuously with small changes in 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 the 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. Hence, even small changes can have quite a dramatic effect on the industry equilibrium.

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

[16] 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).

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. Indeed, 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 could have interpreted our policy instrument as changing the scope of protection on product innovation, here we could interpret our experiments as considering how protection of process innovations, which could result in differences in the speed with which developments can be made to products, affect our results. The 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 and are protectable by other means, such as secrecy.[17]

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 $\theta_i \geq 2.55cr \qquad t_i(t_j) = t_j + (1/r) + c/\theta_i + [(\theta_j-\theta_i)/\theta_i]t_j$

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

[17] The concept of technological trajectories, put forward by Dosi (1982) would be related to this difference in innovation "routes" as well. Also see Choi (1993), who develops this idea in a model of intellectual property rights and R&D competition.

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. In other words, improving the research architecture in a firm need not imply that the firm will introduce a product sooner in equilibrium. 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. Hence, the effect on entry time of a firm's investments in research ability depends on the level of ability that prevailed before the investment. In the former case, the quality of the leader's good must be lower than the quality of the product introduced by its more proficient competitor. In the latter case, 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 unique equilibrium is such that the most able firm enters the market first. Parameter ranges for which the least able firm moves first in the unique equilibrium also exist.

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 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 of entry 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 date, 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 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.[18]

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 a "pre-emptive" to a "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, 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 crucially depends on the fact that both the timing of entry and the identity of the

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

first mover are determined endogenously in our model, contrary to much of the rest of the literature on "strong" patents.

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.

The picture we draw of both minimum quality standards and novelty requirements is one where the effects are very industry and time specific. This is not necessarily bad news for the way these instruments are applied currently. Indeed, many minimum quality standards are industry specific and are regularly revised and updated. Our modelling generally supports this approach. Novelty requirements are applied in a much more uniform manner across industries in theory, although there clearly is some variation across technological class in how the "standard" novelty requirements actually are applied. Still, our model is less supportive of this approach. Second, the picture we draw is that both policy instruments can have significant effect on the order of entry, the absolute level and the relative levels of profit across industry competitors even when only small adjustments in these instruments are made. Indeed, the fact that the order of entry can be so strongly affected, and affects our welfare results, suggests that the approach of setting an exogenous order of entry in a model of novelty requirements may not be desirable—particularly as entry is undoubtedly endogenous in reality at least to some degree.

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Appendix

We begin with the proof of the results for the symmetric case. Since the conditions for the existence of a unique sub-game perfect equilibrium in such a set up have been established formally elsewhere (e.g. Dutta et al., 1995), we take the shortcut of conducting the analysis directly in continuous time.

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

Define the lag chosen by follower i in response to an entry date t_j by the leader j as $\varphi_i \equiv t_i^f - t_j$. For a given date t_j, the profits of the follower depend on the time φ that elapses between the leader's entry and the entry of the follower. If φ_i is small ($\varphi_i \leq \frac{3c}{\theta}$), then the quality of the follower's product is not much higher than the quality of the leader's product and both firms keep positive market shares. In this case, the profits of the follower are given by $\pi_{ia} \equiv \frac{e^{-rt}}{r}\frac{c}{2}[1+\frac{\theta\varphi}{3c}]^2$. If φ_i is large ($\varphi_i > \frac{3c}{\theta}$), then the follower enjoys such a quality advantage that she serves the whole market, obtaining profits of $\pi_{ib} \equiv \frac{e^{-rt}}{r}(\theta\varphi - c)$.

Note that argmax $\pi_{ia} \equiv \varphi_{ia} = \frac{2}{r} - \frac{3c}{\theta}$ and argmax $\pi_{ib} \equiv \varphi_{ib} = \frac{1}{r} + \frac{c}{\theta}$. 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. We must now determine over which range of parameters φ_{ia} and φ_{ib} do indeed represent the follower's best response to the leader's date of entry. The first step consists in determining whether the argmax of each of the two profit functions does indeed fall within the range of φ_i for which the corresponding profit function applies. As π_{ia} is the correct profit function only for $\theta\varphi_{ia} \leq 3c$, we can substitute for φ_{ia} to assert that φ_{ia} is a candidate best response only if $\frac{\theta}{r} < 3c$. Similarly,

π_{ib} is the correct profit function only for $\theta\varphi_{ib} > 3c$ so that, also by substitution, φ_{ib} is a candidate best response function only if $\frac{\theta}{r} \geq 2c$. Note also the case that $\varphi_{ai} \geq 0$ if and only if $\frac{\theta}{r} \geq 1.5c$. Hence, if $\frac{\theta}{r} < 1.5c$ the follower is never willing to wait once the first product is introduced. Since $\varphi_{ia} \geq \varphi_{ib}$ if and only if $\frac{\theta}{r} \geq 4c$, we must consider three cases.

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

Case 2: $2c \leq \frac{\theta}{r} < 3c$. As $\varphi_{ia} < \frac{3c}{\theta}$, φ_{ia} maximises π_{ia} over $\varphi_i \leq \frac{3c}{\theta}$ while φ_{ib} maximises π_{ib} over $\varphi_i > \frac{2c}{\theta}$. To determine the follower's best response, we must compare $\pi_{ia}(\varphi_{ia})$ and $\pi_{ib}(\varphi_{ib})$. Substituting and solving, we have $\pi_{ib}(\varphi_{ib}) > \pi_{ia}(\varphi_{ia})$ 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, develop a drastic innovation and appropriate the entire market rather than share. For parameter ranges below this, the follower chooses to develop an incremental innovation and share the market with the leader.

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

Sketch of the proofs of Lemmas 2 and 3: (Deriving the entry time of the leader, t_{jmax}, that maximises the discounted payoffs, without pre-emption and deriving the pre-emption date, t_p)

The profit function can take one of two forms during the monopoly period depending on whether the quality of the leader's product makes it optimal to serve the whole market. If the leader enters early ($t_j \leq \frac{2c}{\theta}$), then its quality is low, making it optimal to only serve part of the market. For a later date of entry ($t_j > \frac{2c}{\theta}$), the quality of the product is high enough to make it profitable to serve every customer.

The profit function of the leader can also take one of two forms during the duopoly period, depending on whether the follower enters with a drastic innovation ($\frac{\theta}{r} \geq 2.55c$) or prefers to enter with a non-drastic innovation ($\frac{\theta}{r} < 2.55c$). Overall, then, four cases must be considered.

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 does satisfy the initial 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 $t_p=\frac{c}{\theta}+\frac{1}{r}[\frac{e^{\frac{-rc}{\theta}-1}}{1-e^{\frac{-rc}{\theta}-1}}]$. Notice that $t_{j\max}>t_p$ since $e^{\frac{-rc}{\theta}}<\frac{e}{2}$ for the range we consider here. .

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 $t_p=\frac{2}{\theta}[c\frac{\theta}{r}[\frac{e^{\frac{-rc}{\theta}-1}}{1-e^{\frac{-rc}{\theta}-1}}]]^{\frac{1}{2}}>\frac{2c}{\theta}$. This would imply that $t_{j\max}\geq\frac{2c}{\theta}$, which is contrary to the assumption made to define the range of this case.

Case 3: $1.5c\leq\frac{\theta}{r}\leq 2.55c$ 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 $\pi_i^f=2\frac{c}{r}[\frac{\theta}{3rc}]^2Ye^{-rt_j}$ 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 $\frac{\theta}{r}$, with a minimum that we will label $\underline{\theta}$ in what follows. Indeed, numerical computations show that this occurs for $\frac{\theta}{r} \leq 1.804$.

Case 4: $1.5c \leq \frac{\theta}{r} \leq 2.55c$ 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 $1.5c \leq \frac{\theta}{r} \leq 2.55c$,

$$2\frac{Y}{1-Y}[\frac{2\theta}{3rc} - 1] > 1.$$

Sketch of Proof of Proposition 1—the Equilibrium Entry Dates—Including Elements of Proposition 6

We revert to a discrete time approach, where the concept of subgame perfection can be applied rigorously. One should therefore think of the players as choosing dates of introduction on a very fine discrete grid. Since the overall logic of the proofs for the symmetric and asymmetric cases are the same, we present them together. Without loss of generality, consider the 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.

If $t_{pA}<t_{pB}<t_{Amax}<t_{Bmax}$ the following 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.

The argument, roughly, is that 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 in this case. Hence, the profits can be represented by the graph presented in the text for the pre-emption case. Consider the behaviour of the firms up to period t_{Amax}. At least one firm must stop its research no later than t_{Amax} from the definition of this date. Furthermore, 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 the first mover and second mover profits are the same. Since the first mover payoff is increasing over the interval from zero up to t_{pB}, the best response of the first mover is to stop no earlier than t_{pB}. It cannot be best to stop after t_{pB}, as we can conduct a thought experiment that one of the two firms could stop one period before this. At this point, profits would be higher, so that the firm would do better stopping one period earlier. Hence, we can "roll back" the game to t_{pB}. Firm *A* stops earlier than *B*, as *A* would always be willing to pre-empt back to date t_{PA}, which is before t_{pB}. In the symmetric case, 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, $t^*(t_p)$.

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 $\pi_A^l(t_{A\max}) \geq \pi_A^f(t_{B\max})$ while firm B moves first at t_{Bmax} if and only if $\pi_A^l(t_{A\max}) < \pi_A^f(t_{B\max})$. 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.

Briefly, the argument is as follows. 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.

Proof of Proposition 2: Comparison of socially optimal entry date and privately optimal entry date for follower: For $\frac{\theta}{r} \geq 2.55c$, 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 $\frac{\theta}{r} \in]\underline{\theta}, 2.55c[$, 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 $t_B^s > t_B$.

.

Note that if the equilibrium is stand alone so that $\frac{\theta}{r} \in [1.5c, \underline{\theta}]$, 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:

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

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.

For smaller values of $\frac{\theta}{r}$ within the range we consider, however, we can have $\min[[t_{A\max}, t_{pA}] < t_s^l$ so that the minimum quality standard would be ineffective. Indeed, straightforward computations indicate that both cases can occur.
Note that, to be more specific about the ranges over which the leader enters too early or too late, we need to rely on simulations.

Indeed, 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 ranges for which 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 $\frac{\theta}{r} > \underline{\theta}$). 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., $\frac{\theta}{r} > \underline{\theta}$), 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 $\frac{\theta}{r} < \underline{\theta}$), 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 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.

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 $t_p(N$ binding) $\leq t_p(N = 0) < t_s$, a binding *N* must decrease welfare.

We cannot go farther without simulations, however. We can only say that the effects may go either way. Indeed, numerical simulations show that this increases welfare for $\frac{\theta}{r} \in]1.804c, 2.19c[$, while it decreases welfare above this range because entry occurs (socially) too early for $\frac{\theta}{r} \in [2.19c, 2.55c[$.

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 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.)

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. Here, 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. Consider, then, only ranking 4 and apply the minimum quality standard. 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.

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:

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

Where $x = e^{-1}e^{\frac{-rc}{\theta}}$. (For large enough values of $\frac{\theta}{r}$ this is indeed greater than $\frac{2c}{\theta}$. More specifically, numerical computations show that this is greater than $\frac{2c}{\theta}$ for $\frac{\theta}{r} \geq \underline{\theta}$). Let us now assume that $t_{i\max} < \frac{2c}{\theta}$. Under this assumption, it follows that:

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

For the range of values we consider here, this exceeds $\frac{2c}{\theta}$. This is a contradiction. Hence, it follows that $t_{i\max} = \frac{2c}{\theta}$ must hold for the range for which stand alone equilibrium prevails. Numerical computation show that this range is $\frac{\theta}{r} \in]1.5c, \underline{1.804c}[$.

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 $Y = e^{-2}e^{\frac{3rc}{\theta}}$, For our range of values, this is always greater than $\frac{2c}{\theta}$.

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

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

which is satisfied for all $\frac{\theta}{r} > 1.5c$.

4. Comparison of the Different Stopping Times

Based on steps 1, 2 and 3, above, for $\frac{\theta}{r} < \underline{\theta}$, 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 $\underline{\theta} \leq \frac{\theta}{r}$ we have a pre-emptive equilibrium when $t_p < t_{imax}$

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

but this holds, indeed, for this range. Hence, we have a pre-emption equilibrium over this range. Indeed, 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 $\frac{\theta}{r} \leq \overline{\theta}$. This is clearly the case for the parameter range we are considering.