UNIVERSITY-FIRM COMPETITION IN BASIC RESEARCH: SIMULTANEOUS VS SEQUENTIAL MOVES

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University-firm competition in basic research: Simultaneous vs sequential moves

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Abstract

This paper studies the endogenous timing of moves in a game with competition in basic research between a university and a commercial firm. It examines the conditions under which the two entities end up investing in innovation at equilibrium, both under simultaneous and sequential moves. It argues that when the innovation process is not too costly, under any timing, the firm conducts research despite the opportunities for complete free riding. The two sequential move games with either player as leader emerge as equilibrium endogenous timings, with both entities realizing higher profits in either outcome than in a simultaneous move game. Each entity also profits more by following than by leading. Finally, as a proxy for a welfare analysis, we compare the propensities for innovation across the three scenarios and find that university leadership yields a superior performance. This may be used as a selection criterion to choose the latter scenario as the unique outcome of endogenous timing.

Keywords: basic research, endogenous timing, university-firm relations, uncertain innovation.

Jel codes: D21, L13, O31

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1 Introduction

In light of the many externalities associated with know-how, the idea that research and development (R&D) cannot be expected to be provided at adequate levels by the market mechanism is a broadly accepted conclusion in economics (see e.g., Spence, 1984, among others). The sizable gap between the private returns and the social returns to R&D is well-documented (e.g., Griliches, 1995; Bernstein and Nadiri, 1988). In particular, if one focuses solely on basic (or fundamental) research as an isolated component, then the public good aspect and appropriation problems become even more pronounced. As a consequence, the proposition that governments ought to subsidize research is often taken for granted (Hinloopen, 2000).

Over the past decades, an extensive literature has emerged in industrial organization and business strategy, dealing with cooperation in R&D between firms and often also involving universities. The appearance of the so called R&D research joint ventures (RJVs) followed the passage of the National Cooperative Research Act in the U.S. in 1984, but such consortia had existed decades prior to that date in Japan and Europe. Seminal work by Katz (1986) and d' Aspremont and Jacquemin (1988, 1990) on the theoretical analysis of the merits of RJVs led to a burgeoning strand of literature investigating various aspects of inter-firm cooperation in process R&D amongst otherwise competing firms in product markets.[1]

Another literature strand, mostly of an empirical and/or policy-oriented nature but also including some theoretical work, is specifically dedicated to university-firm R&D consortia or RJVs (e.g., Poyago-Theotoky, Beath and Siegel (2002); Hall, Link and Scott (2003); Bercovitz and Feldman (2007); Link and Scott (2005), among others). The Bayh-Dole Act of 1980 was passed to encourage further and deeper collaboration between universities and firms as close partners in R&D and even in the development and commercialization phases of technological progress. Link and Scott (2005) establish empirically that larger RJVs are more likely than smaller RJVs to include a university as a research partner "because larger ventures are less likely to expect substantial additional appropriability problems to result because of the addition of a university partner and because the larger ventures have both a lower marginal cost and a higher marginal value from university R&D contributions to the ventures' innovative output". Based on OECD data, Cabon-Dhersin and Gibert (2019, 2020) report that governments in OECD countries allocate public R&D funding differently between the private and the public

[1] A short list of articles of the broad R&D literature includes Kamien, Muller and Zang (1992), Hinloopen (2000), Amir (2000), Amir et. al. (2003), Chalioti (2015, 2019) and Osório and Pinto (2020).

research sectors (the latter includes universities and public labs) with a greater proportion (at least two-thirds) going to the public sector than to the private sector.

According to Hall et al. (2003), universities tend to be included in industrial projects that involve "new" science with the expectation that the university will provide otherwise scarce research insight that will play a key role in light of the complex nature of the research being undertaken, particularly with regard to the use of basic knowledge. Reinforcing this view, Bercovitz and Feldman (2007) examine the link between firms' innovation strategies and the level of involvement with university-based research. They find that firms with internal R&D strategies leaning toward exploratory activities or facing potential conflicts over intellectual property allocate a greater share of their R&D resources to university research and develop deeper relationships with their university research partners (also see Jaffe, 1989). Many empirical studies have demonstrated that research conducted in public laboratories and universities provide significant benefits to private research (Cohen, Nelson, and Walsh, 2002; and Veugelers and Cassiman, 2005, among others).

The theoretical literature on university-firm relationships explores various aspects of this important nexus that include research and educational quality along with other factors. Cabon-Dhersin and Gibert. (2019, 2020) propose models combining inter-firm spillovers and one-way university-to-firm spillovers to shed light on the socially optimal funding of R&D and its relationship to spillovers, both in cooperative and non-cooperative settings. Hatsor and Zilcha (2020) investigate efficient government subsidization of different classes of universities through student aid and selection. Lahmandi-Ayed, Lasram, and Laussel (2121) study a model of vertical successive monopolies where university graduates form an input to firms that produce for a product market, but focuses on the value of education for the labor market. Del Rey (2001) considers similar issues, but includes research as one of the policy goals. Finally, Correa et al. (2020) consider a political economy approach.[2]

A key characteristic of this literature, in contrast to the aforementioned more established literature on RJVs with its well-known two-stage game, is the absence of a canonical model to account for the complex and multi-faceted university-firm relationship. Recent work by Stenbacka and Tombak (2020) proposed a simple model to capture the strategic interaction between a university and a monopoly firm leading to the determination of their policies concerning basic

[2]Other recent studies on this emerging topic are Lu (2121) and Murra-Anton (2021).

research.[3] A player's decision variable is its probability of success in the uncertain innovation process, which is tied to an R&D cost function with decreasing returns to scale. The university always incurs its research cost, but is rewarded by a fixed government grant only when it is the sole successful innovator in the binary R&D process, in which case it transmits its discovery at no charge to the firm for subsequent development as a monopolist.[4] The firm is rewarded through profits both when it itself succeeds and/or the university succeeds, but must sink their cost of R&D in all cases.

The present paper uses the model developed by Stenbacka and Tombak (2020) and modifies it by introducing a linear term into their quadratic cost function. This modification gets rid of the zero marginal cost of R&D at zero, and thereby paves the way for either player possibly not to conduct any R&D. This paper deals with the possibility that this game of rivalry in basic science might be played with sequential moves and perfect information (thus leading to a Stackelberg equilibrium[5]), rather than with simultaneous moves (i.e., leading to a Nash equilibrium). Rather than exogenously imposing the sequential order and the attending roles of leader and follower to the two entities, we follow a commonly used scheme for an endogenous determination of the proper timing of moves as in Hamilton and Slutsky (1990).[6]

The endogenous timing scheme is based on the premise that a Stackelberg equilibrium will prevail if the corresponding follower prefers her payoff to what she would receive at a Nash equilibrium. Since the leader always prefers her equilibrium payoff to her Nash payoff, a given Stackelberg outcome will prevail if and only if it Pareto dominates the Nash outcome. However, if the would-be follower prefers its Nash payoff, then the outcome will be a Nash equilibrium.[7]

Our main results are as follows. We verify that the basic research game at hand satisfies the conditions for the endogenous emergence of the two possible Stackelberg equilibria, with either player as leader and the other as follower. The university invests more in innovation when it

[3]A related setting of a general public-private relationship under uncertainty is analyzed in Attanasi, My, Buso, and Stenger (2020).

[4]Basic research is sparked by university researchers' innate curiosity about a question. The goal is to expand their knowledge about a topic with possible industrial use and then pass that information on to others. They do not intend to add commercial value to a result.

[5]We use the term Stackelberg equilibrium to indicate subgame-perfect equilibrium in a sequential move game of perfect information (i.e., where the second mover observes the action of the first mover before acting).

[6]This concept has been applied in a number of different applied settings in economics, including Hamilton and Slutsky (1990) for classical duopoly, Leininger (1993) for contests, Kempf and Rota-Grasioza (2010) and Hindriks and Nishimura (2021) for tax competition.

[7]Therefore, rather than imposing an exogenous order of moves, this scheme deduces one on the basis of the players' own choices of when to move.

acts as a leader or a follower in a sequential move game than in a Nash equilibrium, while the firm invests less in its role as a leader or a follower than as a Nash competitor. However, the determination of the identity of a natural leader is not resolved by this scheme as both orders of moves emerge a priori as possible.[8] By the very construction of the endogenous timing scheme, a sequential move outcome reflects the fact that both the leader and the follower in either sequential order of moves enjoy higher profit than they would at the Nash equilibrium (with simultaneous move), as considered by Stenbacka and Tombak (2020). In particular, the concept of endogenous timing rules out simultaneous moves as a plausible outcome. A direct implication of this analysis is that sequential moves emerge as a more plausible timing structure for the basic research game.

In the second part of the paper, we conduct a performance comparison between the three non-cooperative scenarios in terms of their associated probabilities of successful innovation. This measure captures the probability of having at least one successful innovation out of the two independent trials conducted by the two entities in each scenario. As such, it may be taken as a good proxy for the pace of technological progress in basic research. Recall that one important aspect of the model under consideration is that our three scenarios for basic research all suffer from potential social waste in the form of redundant duplication of research effort. The main conclusion of this part is that university leadership leads in terms of the probability of successful innovation, followed by the Nash equilbrium, with firm leadership thus coming in last. In addition, this conclusion also provides a selection criterion to append to the endogenous timing argument, which selects university leadership as being the best outcome out of the three non-cooperative solutions. Since innovation is broadly thought of as being under-supplied from a first-best perspective, this comparison may also be taken as being tantamount to a welfare comparison for the models at hand.

The remainder of this paper is organized as follows. Section 2 describes the model and discusses the payoff functions of each player. It also analyzes the university's and firm's decisions in a simultaneous move game. Section 3 examines both entities' choices in sequential move games when either entity leads and shows that both entities are better off in a Stackelberg setting regardless of which entity becomes the leader. Section 4 compares the probability of successful innovation across the three scenarios. Section 5 concludes.

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[8] Amir and Stepanova (2005) show that Bertrand competition with differentiated products is shown to lead to the same outcome.

2 The mixed duopoly model

This section presents the model of competition in basic research between a single subsidized university and a monopoly firm, along with the objectives of those two entities. It also studies their incentives to invest in basic research and the resulting Nash equilibrium when they compete and make their decisions simultaneously. It discusses their payoffs when both entities find it optimal to undertake basic research or when one of the two entities decides that no investment in innovation is a profit-maximizing strategy.

2.1 The profit functions

The market features a profit-maximizing university or public laboratory (player 1) and a firm (player 2). Both entities compete (simultaneously or sequentially, as will be specified) in basic research whose outcome is uncertain and binary: success and failure are the only two possible outcomes. As in Katsoulacos and Ulph (1998) and more recently in Stenbacka and Tombak (2020), we employ a model in which both entities indirectly decide how much to invest in own basic research by directly choosing the probabilities of success in the innovation process.

Let the university's and the firm's decision variables be their success probabilities in basic research $p \in [0, 1]$ and $q \in [0, 1]$, respectively. We assume that the two entities are equally efficient at conducting basic research, as captured by the common cost function

$$C(p) = kp + \frac{c}{2}p^2 \text{ and } C(q) = kq + \frac{c}{2}q^2,$$

where k and c are positive constants. Because of the linear term in this cost function, the marginal cost of basic research at 0 is not 0 but $k > 0$ and, as a result, one or both entities may well find to their advantage not to conduct any research at all. This is in contrast to the purely quadratic function used in Stenbacka and Tombak (2020), which always leads to a strictly positive probability of innovation. The linear-quadratic cost-of-research function displays diminishing marginal returns to scale. Amir, Halmenschlager & Jin (2011) argue that the linear component of the cost function lowers the magnitude of these returns.[9]

[9] To justify this feature of the cost-of-research function under consideration, Amir, Halmenschlager & Jin (2011) compare its average cost, $k + \frac{c}{2}q$, with the average cost of kq, which is k. While an increase in q will increase the average cost of the former function proportionately, the average cost of the latter function will increase less than proportionately.

Both the university and the firm are assumed to be risk-neutral. The university's expected payoff function is

$$\Pi_1(p, q) = p(1-q)V - kp - \frac{c}{2}p^2. \tag{1}$$

The university focuses on conducting basic research and receives a reward $V > 0$ only if it is the only entity who has succeeded to deliver scientific results. Thus, there is a criterion of scientific novelty in place. V may be thought of as a grant from the government.[10] According to this criterion, the reward V is provided to the university for successful basic research only if the firm's research is unsuccessful. In particular, V is provided by a policymaker who may decide the welfare-maximizing level of funding for the university. The (government) policymaker is not involved in the university's research operations but provides the funding upon successful delivery of scientific results.

The firm maximizes its expected net profit,

$$\Pi_2(p, q) = q\pi + p(1-q)\pi - kq - \frac{c}{2}q^2. \tag{2}$$

Regardless of whether the results of the basic research are the outcome of the successful innovative process undertaken by the firm or the university, it is assumed that the acquired knowledge becomes available to the firm which subsequently adds commercial value to the scientific results and convert them into a new product or service, generating a fixed monopoly profit of $\pi > 0$.[11]

In the present model, the university is required to disclose all scientific results generated during its innovation process when successful. Thus, the university creates scientific knowledge which becomes publicly available and is fully spilled over to the firm. Knowledge spillovers are value-creating but they are directed only one-way from the university to the firm. The firm as a producer of basic research is not subject to the same requirement. The firm can fully absorb its own innovative results. Once the results of basic research are realized, the firm then undertakes applied research in order to design new commercial products or develop technologies that solve a practical problem, resulting in profits for the firm. Even though the stage of converting the results of basic research into a new technology or product is not formally

[10] Note that this is quite different from ex-ante block grants as invoked by Klumpp and Su (2019) in their mixed (vertical) duopoly model.

[11] This profit may be thought of as monopoly profit in a new industry triggered by the discovery and protected by a patent associated with it or as incremental profit for the firm due to process R&D that lowered the unit cost of the firm by a given amount.

modeled, the firm's profit π reflects their commercial value. The first term in (2) captures the firm's expected monopoly profit if the firm succeeds in basic research and the second term represents the benefit appropriated by the firm because of the disclosure requirement imposed on the university when its research alone is successful. The last two terms represent the cost of investing in research.

To guarantee that the equilibrium of the game between the university and the firm is interior, the assumptions $c > 2V$ and $c > 2\pi$ are needed throughout the paper.[12]

Assumption (A): $c > 2V \vee 2\pi$.

This assumption insures that the cost parameter c is high enough so that, for both entities, it is excessively costly to increase the probability of achieving a research success with certainty. This is clearly a reasonable assumption for most research undertakings. Specifically, the cost parameter c needs to be greater than twice the value of a success in basic research for each entity (whichever is higher, V or π).

2.2 Nash equilibrium in basic research

We now explore the university's and firm's incentives to invest in basic research in the hope of achieving an innovation success. The effect of the latter may be seen as lowering the firm's unit cost by a fixed amount (process R&D) or giving rise to a new product. The players simultaneously decide their investment levels. Under this scenario, the tacit assumption here is that research is a priori perfectly appropriable by the firm. A lone success by the university will automatically be transmitted to the firm, something akin to a 100% one-way spillover.

The reaction curves of the firm and the university are, respectively,

$$p(q) = \frac{1}{c}[(1-q)V - k] \vee 0 \text{ and } q(p) = \frac{1}{c}[(1-p)\pi - k] \vee 0.$$

The two reaction curves are downward-sloping, with slopes $-\frac{V}{c}$ and $-\frac{\pi}{c}$, respectively, reflecting that the entities' decisions are strategic substitutes. However, the game has negative externalities for the university (i.e., its payoff function is decreasing in the firm's R&D) but positive externalities for the firm (i.e., its payoff function is increasing in the university's R&D). This

[12]Hereafter, we use the short-hand notation $a \wedge b = \min(a, b)$ and $a \vee b = \max(a, b)$.

asymmetric feature of the game will be important for an intuitive interpretation of several results that follow.

Lemma 1 summarizes the university's and the firm's equilibrium choices and profits as a function of the parameters of the model. With n, we denote the solutions in the simultaneous move game.

Lemma 1 *The Nash equilibrium strategies in basic research* (p_n, q_n) *and their associated payoffs* (Π_1^n, Π_2^n) *are, respectively:*

$$(p_n, q_n) = \begin{cases} \left(\frac{V(c-\pi)-k(c-V)}{c^2-\pi V}, \frac{\pi(c-V)-k(c-\pi)}{c^2-\pi V}\right) & \text{if } k < \frac{\pi(c-V)}{c-\pi} \wedge \frac{V(c-\pi)}{c-V} \\ \left(\frac{V-k}{c}, 0\right) & \text{if } V > \pi \text{ and } \frac{\pi(c-V)}{c-\pi} \leq k < V \\ \left(0, \frac{\pi-k}{c}\right) & \text{if } V < \pi \text{ and } \frac{V(c-\pi)}{c-V} \leq k < \pi \\ (0,0) & \text{if } k \geq \pi \vee V \end{cases}$$

and

$$(\Pi_1^n, \Pi_2^n) = \begin{cases} \left(\frac{cp_n^2}{2}, \frac{cq_n^2}{2} + \pi p_n\right) & \text{if } k < \frac{\pi(c-V)}{c-\pi} \wedge \frac{V(c-\pi)}{c-V} \\ \left(\frac{cp_n^2}{2}, \pi p_n\right) & \text{if } V > \pi \text{ and } \frac{\pi(c-V)}{c-\pi} \leq k < V \\ \left(0, \frac{cq_n^2}{2}\right) & \text{if } V < \pi \text{ and } \frac{V(c-\pi)}{c-V} \leq k < \pi \\ (0,0) & \text{if } k \geq \pi \vee V \end{cases}$$

The Nash equilibrium investment levels reveal that the two entities will not always find it optimal to conduct research. Their decision depends on the relative value of the private return of successful basic research to the firm and the award received by the university, but also on the value of k, which stands for the marginal cost of initial research (i.e., around 0 probability of innovation).

Suppose that $V > \pi$, implying that the benefit from successful research for the university is larger than the benefit for the firm. The parameter k of the linear segment of the cost function also plays a key role. When k is small enough, $k < \frac{\pi(c-V)}{c-\pi}$, both the firm and the university have incentives to invest in basic research, $p_n > 0$ and $q_n > 0$. The firm innovates despite the facts that it enjoys lower returns than the university and can exploit benefits from free-riding. Innovation is costly and the firm could appropriate the benefit π even if it takes the option of not innovating. The university shares all acquired knowledge, which can also be absorbed by the firm. Nevertheless, for low enough costs of research, the firm does find it optimal to compete and conduct innovation itself. The option of free-riding is weak compared to the stronger strategic incentives for the firm to innovate and explore opportunities to profit in the product market. However, it invests less than what the university does, $p_n > q_n$. By allocating more resources to the university (larger V) while the cost of research remains low, the policymaker ensures both entities will find it worthwhile to innovate.

The incentives change when $\frac{\pi(c-V)}{c-\pi} \leq k < V$. For a larger k, only the university invests in basic research, $p_n = \frac{V-k}{c} > 0$ and $q_n = 0$. Investing in research now becomes unprofitable for the firm and the university is the sole producer of knowledge. However, because of the disclosure requirement of any available knowledge acquired by the university, the firm still benefits from research. Research in the public sector is expanded, $p(q = 0) > p(q > 0)$, while that in the private sector is eliminated. Finally, when R&D is overly costly as reflected in $k \geq \pi \vee V$, neither the university nor the firm have any incentive to conduct research. This possibility is obviously a consequence of the novel presence of the linear term in the R&D cost function.

When the firm's monopoly benefit π exceeds the reward provided to the university in case of successful basic research, $\pi > V$, the entities' equilibrium incentives are reversed. For low costs where both firms innovate, $k < \frac{V(c-\pi)}{c-V}$, the firm invests more than what the university does, $p_n < q_n$. The firm is eager to undertake more innovation in an attempt to increase the probability of successful research. Provided that successful basic research is now more valuable to the firm than the university, free-riding on the university's research becomes even less appealing for the firm than in the case where $V > \pi$.

For an extensive cost of research, $\frac{V(c-\pi)}{c-V} \leq k < \pi$, the firm now becomes the sole producer of knowledge, $p_n = 0$ and $q_n = \frac{\pi-k}{c} > 0$. The funding provided to the university is not sufficient to make the innovation process profitable. Thus, the university becomes better off by not investing. The private sector now is expanded at the expense of the public sector. Under-funding the university allows the private sector to dominate the market. From the social perspective, the policy-maker also lacks the benefits generated by knowledge disclosed by the university to the firm. For $\pi \leq k$, neither entity wishes to invest in basic research. The innovation process is so costly that there are no possibilities to benefit from it.

In the range of k where both entities have incentives to engage in innovation, each entity benefits and realizes positive profits. An interesting case arises when both entities receive the same benefit from its innovative activity, $V = \pi$. Despite the fact that in equilibrium, both firms undertake the same investment levels, $p_n = q_n$, and thus incur the same costs, the firm experiences higher profits than the university, $\Pi_1^n < \Pi_2^n$. When successful, the university discloses all research outcomes from its innovation process to the firm for its private use. Thus, the firm fully appropriates these results and acquires applied research to commercialize the outcomes from basic research. The value added to the outcomes from basic research through commercialization generates profits for the firm that are not realized by the university. This additional benefit from innovation is captured solely by the firm. Thus, when the value of basic research is the same for both entities, the firm that receives the know-how realizes higher profits than the university that generated it.

3 The model with sequential moves

This section explores the merits of considering a Stackelberg version of the game without imposing exogenously the roles of leader and follower to the two entities. The goal is to identify the proper sequencing of moves for the game between the university and the firm by invoking a notion of endogenous timing. To this end, we follow the model with observable delay of Hamilton and Slutsky (1990), the salient features of which are summarized next.

3.1 The general endogenous timing scheme

The model with observable delay is based on an extension of the initial game (the basic research game in the present model) by adding a preplay stage to it. At this stage, players simultaneously decide whether to move early or late in the initial game. Then, the timing decisions are revealed and the game is played according to these announcements: if both players choose the same timing, the simultaneous move game is played; if timing decisions are different, sequential play under perfect information - with the order of moves as announced by the players - prevails.[13] Thus, a subgame perfect equilibrium (SPE) of the extended game endogenously determines the equilibrium concept for the initial game.[14]

The extended game thus possesses four different subgames, each following the four possible choices in the preplay stage, namely $(E, E), (E, L), (L, E)$,and (L, L), where E and L indicate that the players have decided to move early or late. The payoff matrix at the preplay (or first)

[13]For a game tree representation of the extended game, see Hamilton and Slutsky (1990) or Amir and Grilo (1999).

[14]According to this scheme, a player cannot unilaterally choose to be a leader or a follower, but may elect not to be a follower simply by deciding to move early in the preplay stage, or not to be a leader by deciding to move late.

stage is given by

		Firm	
		E	L
University	E	(Π_1^n, Π_2^n)	$\left(\Pi_1^l, \Pi_2^f\right)$
	L	$\left(\Pi_1^f, \Pi_2^l\right)$	(Π_1^n, Π_2^n)

The choices (E, E) and (L, L) correspond to a game of basic research with simultaneous moves (Nash). The choices (E, L) and (L, E) correspond to a game of basic research with sequential moves (it will be referred as Stackelberg, hereafter). We denote S_1 and S_2 the Stackelberg equilibrium with the university and the firm as leader, respectively.

An elementary analysis of the 2x2 payoff matrix reveals the following SPE of the extended game that are possible.

Proposition 1 *Every (pure-strategy) Nash equilibria of the above 2x2 matrix game induces a corresponding SPE of the extended game as follows:*

(i) if each entity prefers its Nash payoff to its follower payoff ($\Pi_1^n > \Pi_1^f$ and $\Pi_2^n > \Pi_2^f$), then both entities choose E and the game proceeds with simultaneous moves.

(ii) if each entity prefers its follower payoff to its simultaneous move payoff ($\Pi_1^n < \Pi_1^f$ and $\Pi_2^n < \Pi_2^f$), the outcome is a sequential move game with either order of moves, i.e., $S_1 \cup S_2$.

(iii) if the university (say) prefers its Nash payoff to its follower payoff while the opposite holds for the firm ($\Pi_1^n > \Pi_1^f$ and $\Pi_2^n < \Pi_2^f$), then (E, L) implying that sequential moves with the university as leader prevails (i.e., S_1).

Since, for any game, the leader is always better off than at a Nash equilibrium (i.e., $\Pi_1^l > \Pi_1^n$ and $\Pi_2^l > \Pi_2^n$), part (ii) implies that the entities will play a sequential move game when the would-be follower enjoys larger profits than in a Nash equilibrium. In such cases, moving sequentially is thus a Pareto improvement for both entities. To check whether either player may prefer its follower payoff to its Nash payoff, we now consider S_1 and S_2 separately for our game of basic research.

3.2 Stackelberg model with the university as leader (S_1)

We analyze the players' choices in the sequential move two-stage game (of perfect information) where the university chooses its investment level in basic research first and the firm follows (i.e., subgame (E, L)). For any decision p made by the university (leader), the firm (follower) chooses q to maximize its profit, upon observing the university's choice. In a practical sense, since the university's choice is formally a probability, we may specify that the firm actually observes the university's R&D investment and then backs out the corresponding success probability. It is important to specify that the *actual realization* of the university's probability choice is not observed by the firm before it makes its own decision.[15] This may be justified by the realistic feature that such an R&D process typically requires a long time before a binary conclusion of success or failure can be assessed. Thus, what the firm as follower reacts to in a sequential game is a committed announcement by the university of its R&D investment. Subsequently, the two entities would actually conduct research over time periods with substantial overlap.

The firm's best response function is $q(p) = \frac{1}{c}\left[\pi(1-p) - k\right]$. The university anticipates this optimal reaction by the firm and moves first to maximize its payoff conditional on the firm's best response $q(p)$. Lemma 2 highlights the equilibrium investment levels chosen by the university and the firm when the former leads the game. With l and f, we denote the role of each entity as a leader and a follower.

Lemma 2 *When the university is the leader, the Stackelberg equilibrium decisions in basic research (p_l, q_f) and their associated payoffs $\left(\Pi_1^l, \Pi_2^f\right)$ are, respectively:*

$$(p_l, q_f) = \begin{cases} \left(\frac{(V(c-\pi)-k(c-V))}{c^2-2\pi V}, \frac{\pi\left(c^2-V(\pi+c)\right)-k\left(c^2-\pi(V+c)\right)}{c(c^2-2\pi V)}\right) & \text{if } k < \frac{\pi\left(c^2-V(\pi+c)\right)}{c^2-\pi(V+c)} \wedge \frac{V(c-\pi)}{c-V} \\ \left(\frac{V-k}{c}, 0\right) & \text{if } V > \pi \text{ and } \frac{\pi\left(c^2-V(\pi+c)\right)}{c^2-\pi(V+c)} \leq k < V \\ \left(0, \frac{\pi-k}{c}\right) & \text{if } V < \pi \text{ and } \frac{V(c-\pi)}{c-V} \leq k < \pi \\ (0,0) & \text{if } k \geq \pi \vee V \end{cases}$$

and

$$\left(\Pi_1^l, \Pi_2^f\right) = \begin{cases} \left(\frac{c^2-2\pi V}{2c}p_l^2, \frac{cq_f^2}{2} + \pi p_l\right) & \text{if } k < \frac{\pi\left(c^2-V(\pi+c)\right)}{c^2-\pi(V+c)} \wedge \frac{V(c-\pi)}{c-V} \\ \left(\frac{cp_l^2}{2}, \pi p_l\right) & \text{if } V > \pi \text{ and } \frac{\pi\left(c^2-V(\pi+c)\right)}{c^2-\pi(V+c)} \leq k < V \\ \left(0, \frac{cq_f^2}{2}\right) & \text{if } V < \pi \text{ and } \frac{V(c-\pi)}{c-V} \leq k < \pi \\ (0,0) & \text{if } k \geq \pi \vee V \end{cases}$$

[15] Indeed, otherwise, the firm would respond to an observed success of the university by actually investing zero in R&D.

In line with the Nash case, when the value of successful research for the university exceeds its value for the firm, $V > \pi$, for relatively low costs of innovation, both firms find it optimal to invest in research. For higher costs, only the university conducts research, while for even higher costs, both firms quit. When firm's monopoly profits generated from successful innovation exceeds its benefit to the university, $V < \pi$, there is a cost level where only the firm conducts research. For lower costs, both entities do, while for higher costs, neither the firm nor the university innovates.

The comparison of the equilibrium investment levels in the sequential move and simultaneous move games reveals that both players are better off when they compete in a Stackelberg fashion than Nash. Suppose that the cost of innovation is low enough so that both entities have incentives to invest in order to increase the probability of successful research. The university as leader invests more than in the Nash setting, $p_l > p_n$, while the firm as follower invests less, $q_f < q_n$. As leader, the university also invests more than the firm, seeking to increase the probability of a successful research outcome and be able to receive the reward by the policymaker. Due to the nature of the strategic interactions and since the firm as follower has weaker incentives to invest in innovation, its probability of success will also be smaller, $p_l > q_f$. The firm is able to observe the university's investment choice. Free riding effects are present and stronger than in the simultaneous move game where the firm cannot observe the university's investment levels and thus its probability of achieving successful results. Therefore, as a follower, the firm can free ride on the university's research, provided that the university leads and invests significantly in innovation. For higher costs, there is a sole investor in basic research, and thus the analysis is as in subsection 2.2.

For low enough costs of innovation so that conducting basic research is optimal, both entities enjoy higher equilibrium profits when they interact in a game with a leader/follower structure than when they make their decisions simultaneously, $\Pi_1^l > \Pi_1^n$ and $\Pi_2^f > \Pi_2^n$ (as will be formally shown shortly). Both entities wish to get involved in the sequential move game where the university has the lead. The firm who is following benefits from the increase in research undertaken by the university because it is spilled over to the firm, if successful. Because of free riding, the firm invests less in innovation itself resulting in considerable cost savings. In turn, the firm enjoys higher profits in her role as a follower than as a Nash competitor.

3.3 Stackelberg model with the firm as the leader (S_2)

We now determine the equilibrium decisions when the firm acts as a leader and chooses its investment level before the university does as follower (i.e., subgame (L, E)). The firm takes into consideration the university's best response function $p(q) = \frac{1}{c}[V(1-q)-k]$, and moves first, choosing the level of R&D that maximizes its profit. The university then observes the firm's R&D investment (but not the actual realization of a success or failure, as described in detail in the previous subsection) and follows by making its own investment choice. Lemma 3 states the resulting SPE investment levels.

Lemma 3 *When the firm is the leader, the Stackelberg equilibrium choices in basic research* (p_f, q_l) *and their associated payoffs* $\left(\Pi_1^f, \Pi_2^l\right)$ *are, respectively:*

$$(p_f, q_l) = \begin{cases} \left(\frac{Vc(c-\pi)-k\left(c^2-V(\pi+c)\right)}{c(c^2-2\pi V)}, \frac{\pi(c-2V)-k(c-\pi)}{c^2-2\pi V}\right) & \text{if } k < \frac{\pi(c-2V)}{c-\pi} \wedge \frac{V\left(c^2-\pi c\right)}{c^2-V(\pi+c)} \\ \left(\frac{V-k}{c}, 0\right) & \text{if } V > \frac{\pi c}{\pi+c} \text{ and } \frac{\pi(c-2V)}{c-\pi} \leq k < V \\ \left(0, \frac{\pi-k}{c}\right) & \text{if } V < \frac{\pi c}{\pi+c} \text{ and } \frac{V\left(c^2-\pi c\right)}{c^2-V(\pi+c)} \leq k < \pi \\ (0,0) & \text{if } k \geq \pi \vee V \end{cases}$$

and

$$\left(\Pi_1^f, \Pi_2^l\right) = \begin{cases} \left(\frac{cp_f^2}{2}, \frac{(c(\pi-k)+\pi k)q_l}{2c} + \pi p_f\right) & \text{if } k < \frac{\pi(c-2V)}{c-\pi} \wedge \frac{V\left(c^2-\pi c\right)}{c^2-V(\pi+c)} \\ \left(\frac{cp_f^2}{2}, \pi p_f\right) & \text{if } V > \frac{\pi c}{\pi+c} \text{ and } \frac{\pi(c-2V)}{c-\pi} \leq k < V \\ \left(0, \frac{cq_l^2}{2}\right) & \text{if } V < \frac{\pi c}{\pi+c} \text{ and } \frac{V\left(c^2-\pi c\right)}{c^2-V(\pi+c)} \leq k < \pi \\ (0,0) & \text{if } k \geq \pi \vee V \end{cases}$$

When the university's reward from successful basic research V is larger than $\frac{\pi c}{c+\pi}$, for substantially low costs of investment, $k < \frac{\pi(c-2V)}{c-\pi}$, both entities are active in equilibrium (with strictly positive probabilities). For higher costs, the firm as leader chooses to quit and let the university as follower innovate. The firm will be able to absorb the innovation and make profits through commercialization, even though it does not do any research itself. However, if the university's reward is smaller than $\frac{\pi c}{c+\pi}$, and the cost of investment is low enough, the opposite holds. The firm leads and becomes the sole producer of basic research. The university follows and chooses not to invest in innovation. For costs of innovation that exceed the value of research for the two entities, equilibrium calls for no innovation by either.

3.4 Endogenous timing for the basic research game

We now study the players' equilibrium research levels and profits realized in the simultaneous move and the two sequential move games to reach a conclusion about the endogenous timing of the initial research game at hand. Proposition 2 compares the R&D choices across the three different timing structures under consideration.

Proposition 2 *At the respective interior equilibria of the three games with different timing structures,*

(i) the university ranking of its equilibrium investment levels is $p_f > p_l > p_n$*;*

(ii) and the firm's ranking of its equilibrium investment levels is $q_l < q_f < q_n$.

Proposition 2 establishes that the university has stronger incentives to do basic research in a sequential move game, regardless of the sequence of moves, while the firm conducts the highest level of research in a simultaneous move game.

The next result highlights that, for each player, both its profits as leader *and as* follower in the respective sequential move games exceed its Nash equilibrium profits.

Proposition 3 *At interior equilibria, the university and the firm share the same ranking of their respective payoffs across the three games with different timing structures: follower payoff exceeds leader payoff, which in turn, exceeds the payoff of a Nash competitor,*

$$\Pi_1^f > \Pi_1^l > \Pi_1^n \text{ and } \Pi_2^f > \Pi_2^l > \Pi_2^n. \tag{3}$$

Therefore, the endogenous timing outcome for the basic research game is $S_1 \cup S_2$*; i.e., both sequential move configurations,* (E, L) *and* (L, E).

According to Proposition 3, this endogenous timing conclusion follows directly from the facts that both the university and the firm experience larger payoffs in a sequential move game, with either sequence of moves, compared to a Nash equilibrium. In other words, regardless of the order of the moves, both entities are better off when they compete sequentially than simultaneously. This holds true irrespective of the role that each player has. Either can serve as a leader or a follower preserving higher profits for both entities. A further selection argument that will justify the Stackelberg equilibrium with the university as leader as unique outcome will be provided in the next section.

Proposition 3 also allows us to settle the issue of first-mover versus second-mover advantage for both players in the basic research game. Recall that, in contrast to endogenous timing, this concept involve comparisons of payoffs between the two Stackelberg equilibria only, and not between Stackelberg and Nash equilibria. While this concept is most often defined for symmetric games, it is of interest to note that it can be meaningfully settled in our intrinsically asymmetric game. Since each of the two players prefers being a follower to being a leader, according to Proposition 3, the research game is characterized by a second-mover advantage for both players.

Acting as a leader, the university invests more in basic research and performs better than as a Nash competitor. Higher investment by the university also benefits the firm who can appropriate outcomes of successful research. Thus, the firm as follower wishes the university to lead and invest more in innovation. The positive externality from the university's research to the firm will also result in higher profits for the firm. Provided that the firm now invests less, there will also be cost savings that will increase the firm's profits even further. Thus, the firm as follower, will prefer to experience its Stackelberg payoff than its payoff in a Nash equilibrium.

The firm will choose to invest less in basic research also when it acts as a leader. It will find it optimal to restrict its own investment and induce its follower to invest more heavily (due to strategic substitutes). By doing so, the university will increase the probability of achieving a successful outcome, which will be directed to the firm, creating profits. Thus, lower investment levels and higher profits are anticipated by the firm, when acting as a Stackelberg leader.

The university, either as a leader or a follower, will conduct more research than under simultaneous moves and the fact that this will be spilled over to the firm (if the latter is unsuccessful) is certainly quite appealing. This will benefit both players. Thus, getting involved in a sequential move game conveys an advantage to both entities in the basic research game. The resulting Pareto improvement over the simultaneous move game provides a compelling justification for the emergence of a Stackelberg equilibrium in this context.

In general, endogenous timing depends on whether the decision variables are strategic substitutes or complements and on whether the payoffs have positive or negative externalities. The latter is reflected in how the set of actions that represent higher profits for the players is related to the reaction functions. Hamilton and Slutsky (1990) argue that if both reaction functions have slopes of the same sign, there are two possible cases: (a) neither reaction function intersects the set of outcomes that represent higher profits for both Stackelberg players to the simultaneous move outcome, or (b) both reaction functions enter this set. In our model, the latter holds.

Graphically, the Nash equilibrium of a simultaneous move game is at the intersection of the two players' reaction functions and the set of actions that yield higher profits for both entities lie in the intersection of the iso-profit curves that go through the Nash point. In our model, both reaction functions are downward sloping and, due to positive (negative) externalities for the firm (university), the set that represents an improvement for both entities lies in the fourth quadrant (South-East of the Nash point). Both reaction functions enter this set. Downward sloping reaction functions imply that increases in investment by one entity triggers a decrease in the other's action. Figure 1 shows the players' iso-profit curves and their reaction functions. It also marks the Pareto improvement outcomes for both players. In a sequential move game, the leader chooses its most preferred point on the follower's reaction function. That is the point where the leader's iso-profit curve that represents higher profits than in a Nash equilibrium is tangent to the follower's best reaction function.

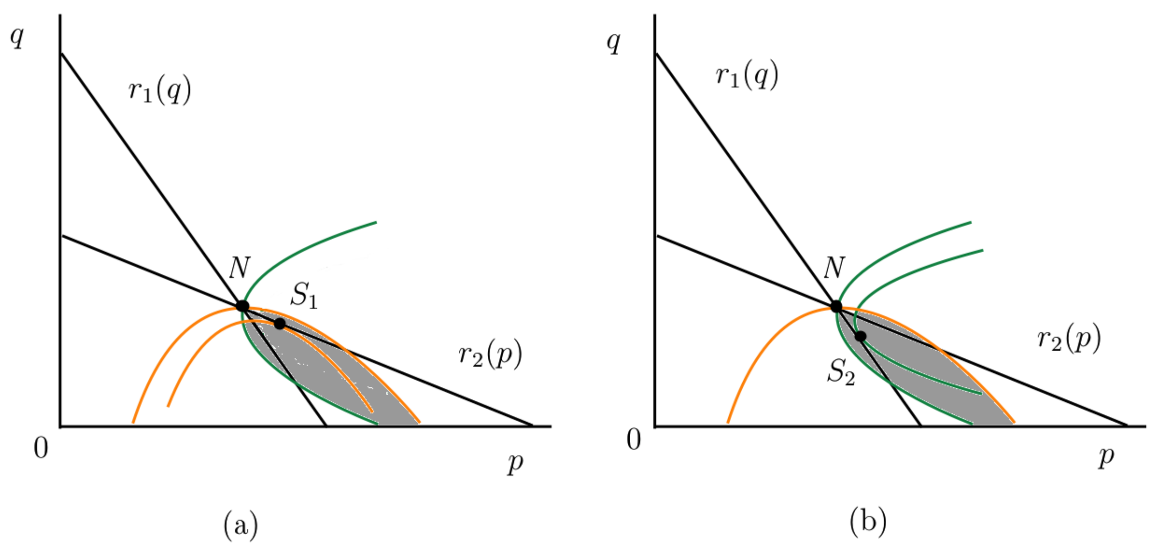

Figure 1: The university's and firm's reaction functions are indicated as $r_1(q)$ and $r_2(p)$, respectively. The university's iso-profit curves are marked with orange and the firm's iso-profit curves are marked with green. We highlight with gray the area that represents higher profits for both entities compared to a Nash equilibrium. The university leads in figure (a) while it follows in figure (b).

Due to positive (negative) externalities for the firm (university), each iso-profit function is monotone in the other entity's decision. Hence, since both reaction functions slope down and an increase in the university's investment increases the firm's profit as moving along the latter's reaction function, each entity prefers to be a Stackelberg player - acting either as leader or as follower - to playing simultaneously.

The comparison of the two Stackelberg configurations offers insights into the roles of a leader and a follower. In our model, each entity profits more by following than by leading. For example, consider the case where the firm acts as a Stackelberg leader. The firm chooses an investment level that is associated with the tangency point between a firm's iso-profit curve and the university's reaction function. Provided that the university's reaction function is steeper, the firm will decrease its own investment by more than the increase in the university's investment. In turn, the university will move to a lower iso-profit curve than what it could do as a leader, implying higher profits, $\Pi_1^l < \Pi_1^f$. As a Stackelberg leader, the firm will also earn lower profits than as a follower, $\Pi_2^f > \Pi_2^l$. Thus, in our model, each entity experiences a greater payoff improvement (over the Nash equilibrium outcome) as a Stackelberg follower than as a leader.

4 Comparing propensities for innovation

A key characteristic of each of the solutions under consideration is what one might refer to as the propensity for innovation in basic research, or a measure of the speed of technological progress in this context. Since R&D is typically under-provided in most strategic settings from a social point of view (Griliches, 1995; Bernstein and Nadiri, 1988), the propensity for R&D may be taken as a good proxy for a social welfare analysis.[16]

To propose a meaningful version of such a concept, we observe that the three non-cooperative solutions reflect some duplication of R&D embedded in the fact that, whenever both entities succeed in innovating, one of the successes is simply redundant. Yet, making two attempts to innovate increases the overall probability of (at least one) success. Thus, in the present setting, the probability of success in innovation appears to be the proper measure of the propensity for innovation in basic research for all the three scenarios under consideration (see Stenbacka and Tombak, 2020). For the three scenarios, this probability is denoted by P_i, where $i = n, 1, 2$ stands for Nash, S_1 and S_2, respectively.

[16] An explicit fully-fledged social welfare analysis would require the specification of basic market primitives, including a demand and cost functions. As such, this is beyond the scope of the present paper.

We now calculate this probability in terms of the two players' choices (p, q). For any one of the three scenarios, given any action vector (p, q) by the two entities, there will be innovation success under each of the three following events: the university succeeds but the firm does not; the firm succeeds but the university does not; and both succeed. The probabilities of these three events to occur are, respectively, $p(1-q)$, $q(1-p)$, and pq. Hence, given the two players' choices (p, q), the probability of success is

$$P = p(1-q) + q(1-p) + pq = p + q - pq,$$

Therefore, the success probabilities for the three non-cooperative solutions are respectively given by

$$P_n = p_n + q_n - p_n q_n,\ P_1 = p_1 + q_1 - p_1 q_1,\ \text{and } P_2 = p_2 + q_2 - p_2 q_2.$$

We now compare the speeds of technological progress (in basic research), as proxied by the corresponding propensities for innovation, across the three scenarios under consideration.

Proposition 4 *The propensities for innovation in basic research across the three different timing structures are ranked as follows:*

$$P_1 > P_n > P_2.$$

Proposition 4 provides one more dimension of interest under which to evaluate the three possible ways to organize the conduct of basic research between a university and a firm. Not surprisingly, university leadership provides the best propensity for R&D. A less expected outcome is that, although firm leadership profit-dominates the simultaneous move game since it is an equilibrium outcome of endogenous timing, this comparison is reversed as far as the propensity for innovation in concerned.

As a final remark on the possible implications of the last result, one can invoke it to complete the endogenous timing argument developed in the previous section. We can use the propensity for innovation as an additional criterion to eliminate the firm leadership outcome. Of the three non-cooperative scenarios, university leadership is the best but firm leadership is the worst, despite its emergence as an equilibrium under endogenous timing.

Corollary 1 *If one imposes higher propensity for innovation as an additional criterion in the* *endogenous timing scheme, then the unique outcome is the Stackelberg equilibrium with the university as leader.*

As a word of caution, observe that using the propensity for innovation as a selection device between multiple equilibria of the extended game lies outside the basic idea behind endogenous timing, in the sense that the latter is grounded in players' individual incentives, and not in any aspect of group rationality.

One of the most important stylized facts about innovation that is widely believed and empirically verified is that innovation is under-supplied from a first-best perspective. In light of this fact, the comparison of the propensities for innovation may also be taken as being representative of a welfare comparison for the three possible timings of the basic research game. Therefore, one may conclude that university leadership dominates the other two scenarios in terms of social welfare.

5 Conclusion

This paper considers a game of competition in basic research. A university and a firm conduct research in order to increase their probability of success in innovation. If the university succeeds in the innovation process, it receives a financial reward by a policymaker and its innovative results are fully spilled over to the firm. The firm can innovate itself but it can also fully appropriate the university's results and profit from them. We compare the two entities' decisions to invest in innovation in a simultaneous move or in a sequential move fashion in order to study endogenous timing in the basic research game. We show that the university invests more heavily in innovation when it acts as a leader or a follower in a sequential move game than in a Nash equilibrium, while the firm invests less in its role as a leader or a follower than as a Nash competitor. However, when the innovation process is not too costly, the firm invests in basic research despite the opportunities for free riding. In fact, both entities would be better off if they engaged in a sequential move game with either sequence of moves (and perfect information), than if they compete with simultaneous moves. It follows that endogenous timing yields the two Stackelberg equilibria as natural outcomes.

We also consider the propensity for innovation which is the probability of at least one success in the research attempts of the two entities. University leadership turns out to yield the highest propensity for innovation, followed by the simultaneous move game, and then firm leadership. Adopting the propensity for innovation as a selection criterion for the endogenous timing exercise therefore yields the conclusion that university leadership is the unique outcome from the social perspective.

Our model suggests new avenues for future theoretical and empirical research. One can examine the optimal degree of knowledge spillovers from the university to the commercial firm. The current one-size-fits-all intellectual property (IP) protection policies may be challenged. A possible suggestion is for the protection policies to distinguish between applied research that has some commercial value and basic research that focuses on big science. Basic research is costly and while its outcomes add to scientific knowledge, they may not possess immediate application. Policies that weaken IP protection of basic research or even encourage coordination and exchange of ideas will allow the innovators to achieve better results. However, the IP protection of applied research can remain strong. Thus, the policy makers may need to take into consideration the different nature of scientific activities. Future studies can also consider competition between firms in the commercial sector and examine how their optimal incentives to innovate change in the presence of competitive pressure and opportunities for free-riding. One can also provide additional insights by considering that the university and the firm have asymmetric costs of conducting research.

A APPENDIX

The proofs of all the results of the paper are contained in this appendix and given in the order in which they appear in the text.

A.1 Proof of Lemma 1

The first-order conditions of the entities' profit maximization are $p = \frac{V-k-Vq}{c}$ and $q = \frac{\pi-k-\pi p}{c}$. The second-order conditions are also satisfied since $\frac{\partial^2 \Pi_1}{\partial p^2} = \frac{\partial^2 \Pi_2}{\partial q^2} = -c < 0$. The solution of the system of first-order conditions yields the interior Nash equilibrium research investments p_n and q_n given in Lemma 1.

We need to show that $p_n \in [0,1]$ and $q_n \in [0,1]$. Given that $c^2 - \pi V > 0$ because of Assumption A, p_n and q_n are less than 1 respectively if and only if $(c+k)(V-c) < 0$ and $(c+k)(\pi - c) < 0$, which is true.

The probabilities p_n and q_n are also strictly positive if and only if $k < \frac{V(c-\pi)}{c-V}$ and $k < \frac{\pi(c-V)}{c-\pi}$, respectively. When $k \geq \frac{V(c-\pi)}{c-V}$, the university's investment is equal to 0 and the firm responds optimally by choosing $\frac{\pi-k}{c}$ which is strictly positive for $\pi > k$. We can check that the university's best response to $\frac{\pi-k}{c}$ is 0. So, when $k \geq \frac{V(c-\pi)}{c-V}$, $p_n = 0$ and $q_n = \frac{\pi-k}{c} > 0$, provided that $\pi > k$. We can also show that when $k \geq \frac{\pi(c-V)}{c-\pi}$, we have $p_n = \frac{V-k}{c} > 0$, provided that $V > k$ and $q_n = 0$.

Notice that the constraint on k is less restrictive for the university than for the firm when $V > \pi$. That is when $V > \pi$ and $\frac{V(c-\pi)}{c-V} > \frac{\pi(c-V)}{c-\pi}$. When $V = \pi$, there is an interior solution $p_n = q_n = \frac{V-k}{V+c}$, provided that $k < V = \pi$. Otherwise, $p_n = q_n = 0$.

A.2 Proof of Lemma 2

Inserting the best response function of the firm in the objective function of the university, the university's problem becomes $\max_p p\,(1 - q\,(p))\,V - \frac{c(p)^2}{2} - kp$. The first order condition yields $p_l = \frac{V(c-\pi)-k(c-V)}{c^2-2\pi V}$ (the second-order condition $\frac{2\pi V - c^2}{c} < 0$ is satisfied by Assumption A).

We have $p_l > 0$ if and only if $k < \frac{V(c-\pi)}{c-V}$; and $p_l < 1$ if and only if $V\,(\pi + c) - c^2 - k\,(c - V) < 0$ which holds true because $V\,(\pi + c) - c^2 < 0$ (by Assumption A) and $-k\,(c - V) < 0$. Hence, for $0 \leq k < \frac{V(c-\pi)}{c-V}$, the firm chooses $q_f = \frac{1}{c}\,(\pi\,(1 - p_l) - k) = \frac{\pi\left(c^2 - V(\pi+c)\right) - k\left(c^2 - \pi(V+c)\right)}{c(c^2-2\pi V)}$. The inequalities $c\,(c^2 - 2\pi V) > 0$, $c^2 - V(\pi + c) > 0$, and $c^2 - \pi\,(V + c) > 0$ hold (given $c > 2\pi$ and $c > 2V$), implying that $q_f > 0$ if and only if $k < \frac{\pi\left(c^2 - V(\pi+c)\right)}{c^2 - \pi(V+c)}$. Also, $q_f < 1$ if and only if

$\pi\left(c^2 - V(\pi + c)\right) - k\left(c^2 - \pi\left(V + c\right)\right) - c\left(c^2 - 2\pi V\right) < 0$. This condition can be rewritten as $\left(c - \pi\right)\left(\pi V - c^2\right) + k\left(\pi\left(V + c\right) - c^2\right) < 0$, which holds by Assumption A.

It is easy to see that $\frac{\pi\left(c^2 - V(\pi+c)\right)}{c^2-\pi(V+c)} \gtrless \frac{V(c-\pi)}{c-V}$ when $\pi \gtrless V$. So, if $\pi < V$ and $k \geq \frac{\pi\left(c^2-V(\pi+c)\right)}{c^2-\pi(V+c)}$, then the firm chooses an investment equal to 0. The university's objective function becomes $pV - \frac{c(p)^2}{2} - kp$ and in this case, the university chooses $p_l = \frac{V-k}{c}$ provided that $k < V$. Also, if $\pi > V$ and $k \geq \frac{V(c-\pi)}{c-V}$, then $p_l = 0$ and $q_f = \frac{\pi-k}{c}$ provided that $k < \pi$.

A.3 Proof of Lemma 3

The firm is the leader and maximizes $\Pi_2\left(q, p\right) = q\pi + \left(1 - q\right)p\left(q\right)\pi - \frac{c}{2}\left(q\right)^2 - kq$. Its first order condition yields $q_l = \frac{\pi(c-2V)-k(c-\pi)}{c^2-2\pi V}$. The second-order condition is also satisfied: $\frac{2\pi V - c^2}{c} < 0$. We have $q_l > 0$ if and only if $k < \frac{\pi(c-2V)}{c-\pi}$, and $q_l < 1$ if and only if $\left(c + k\right)\left(\pi - c\right) < 0$, which holds true under the assumption $c > 2\pi$. Thus, for $0 \leq k < \frac{\pi(c-2V)}{c-\pi}$, the university as follower chooses

$$p_f = \frac{1}{c}\left(V\left(1 - q_l\right) - k\right) = \frac{V\left(c^2 - \pi c\right) - k\left(c^2 - V\left(\pi + c\right)\right)}{c\left(c^2 - 2\pi V\right)}.$$

Provided that $c\left(c^2 - 2\pi V\right) > 0$, $c^2 - \pi c > 0$, and $c^2 - V\left(\pi + c\right) > 0$ by assumptions $c > 2V$ and $c > 2\pi$, we have $p_f > 0$ if and only if $k < \frac{V\left(c^2-\pi c\right)}{c^2-V(\pi+c)}$, and $p_f < 1$ if and only if $V\left(c^2 - \pi c\right) - k\left(c^2 - V\left(\pi + c\right)\right) - c\left(c^2 - 2\pi V\right) < 0$. The last condition can be rewritten as $\left(c + k\right)\left(V\left(\pi + c\right) - c^2\right) < 0$, which holds true.

We can also show that $\frac{V\left(c^2-\pi c\right)}{(c^2-V(\pi+c))} \gtrless \frac{\pi(c-2V)}{c-\pi}$ when $V \gtrless \frac{\pi c}{\pi+c}$. Thus, if $V < \frac{\pi c}{\pi+c}$ and $k \geq \frac{V\left(c^2-\pi c\right)}{(c^2-V(\pi+c))}$, the university (the follower) chooses an investment equal to 0. The firm's objective function becomes $q\pi - \frac{c(q)^2}{2} - kq$ and the university chooses $q_f = \frac{1}{c}\left(\pi - k\right)$ provided that $k < \pi$. Also, if $V > \frac{\pi c}{\pi+c}$ and $k \geq \frac{\pi(c-2V)}{c-\pi}$, then $q_l = 0$ and $p_f = \frac{V-k}{c}$ provided that $k < V$.

A.4 Proof of Proposition 2

We compare interior equilibrium investments in basic research in the three different games (Nash, Stackelberg S^1 and Stackelberg S^2), that is under

$$k < \min\left(\frac{V\left(c^2 - \pi c\right)}{c^2 - V\left(\pi + c\right)}, \frac{\pi\left(c - 2V\right)}{c - \pi}, \frac{\pi\left(c^2 - V(\pi + c)\right)}{c^2 - \pi\left(V + c\right)}, \frac{\pi\left(c - V\right)}{c - \pi}, \frac{V\left(c - \pi\right)}{c - V}\right).$$

Regarding the university, we get $p_l - p_n = \frac{\pi V(V(c-\pi)-k(c-V))}{(c^2-\pi V)(c^2-2\pi V)}$. The denominator is strictly positive by Assumption A and since k has to be smaller than $\frac{V(c-\pi)}{c-V}$, the numerator is also strictly positive. Hence, $p_l > p_n$. We also have $p_f - p_l = \frac{\pi V k}{c(c^2-2\pi V)}$ which is strictly positive. So, the university's ranking is $p_f > p_l > p_n$. As for the firm, $q_n - q_f = \frac{\pi^2 V(V(c-\pi)-k(c-V))}{c(c^2-\pi V)(c^2-2\pi V)}$, is strictly positive by Assumption A and the constraint $k < \frac{V(c-\pi)}{c-V}$. We also have $q_f - q_l = \frac{\pi V(c+k-\pi)}{c(c^2-2\pi V)}$, which is strictly positive. Hence, the firm's ranking is $q_n > q_f > q_l$.

A.5 Proof of Proposition 3

Starting from the university's follower payoff, we have $\Pi_1(p_f, q_l) > \Pi_1(p_l, q_l)$ since the university is on its (single-valued) reaction curve at S_2. Also, $\Pi_1(p_l, q_l) > \Pi_1(p_l, q_f)$ because of the negative externality and the fact that $q_f > q_l$. Hence, the university has a second-mover advantage.

Since the university as leader has as one feasible option to pick its Nash equilibrium action, thereby forcing the Nash equilibrium outcome (when the follower's reaction curve is single-valued) but chooses instead $p_l \neq p_n$, it follows that $\Pi_1(p_l, q_f) > \Pi_1(p_n, q_n)$. Therefore, $\Pi_1(p_f, q_l) > \Pi_1(p_l, q_f) > \Pi_1(p_n, q_n)$.

For the comparison between Nash and follower payoffs for the firm, we have $\Pi_2(p_l, q_f) > \Pi_2(p_l, q_n)$ since the firm is on its (single-valued) reaction curve at S_1, and $\Pi_2(p_l, q_n) > \Pi_2(p_n, q_n)$ because of the positive externality from the university to the firm and the fact that $p_l > p_n$. Hence, the firm's follower equilibrium payoff (at S^1) is greater than at its Nash equilibrium payoff. We also have $\Pi_2(p_l, q_f) - \Pi_2(p_f, q_l) = \pi^2 V \frac{V(c+k-\pi)^2 - 2k(c+k)(c-\pi)}{2c(c^2-2\pi V)^2}$, which is positive for low values of k so that both entities innovate (interior solution) in the two games under consideration.

A.6 Proof of Proposition 4

The proof proceeds via direct calculation.

We have $P_1 - P_n = \pi V\left[V(c-\pi) - k(c-V)\right] \frac{c^3(c+k)(c-2\pi)+c\pi(3k\pi+c(4\pi-k)-c^2)-\pi^2V^2(c+k+\pi)}{c(c^2-2\pi V)^2(c^2-\pi V)^2}$. The term in the brackets is positive because $k < \frac{V(c-\pi)}{c-V}$, and so is the numerator of the fraction. Thus, $P_1 > P_n$.

We have $P_n - P_2 = \pi V(c+k)^2(c-\pi)\frac{c^4+\pi V^2(3c-\pi)-c^2V(2c+\pi)}{c(c^2-2\pi V)^2(c^2-\pi V)^2}$, which is positive, implying that $P_n > P_2$.

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