And the Winner is – Acquired.

Entrepreneurship as a Contest with Acquisition as the Prize

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Abstract

We analyze an innovation game between one incumbent and a large number of entrants. In the first stage, firms compete to develop innovations of high quality. They do so by choosing, at equal cost, the success probability of their R&D approach, where a lower probability goes along with a higher value in case of success—that is, a more radical innovation. In the second stage, successful entrants bid to be acquired by the incumbent. We assume that entrants cannot survive on their own, so being acquired amounts to a 'prize' in a contest. We identify an equilibrium in which the incumbent chooses the least radical project. Entrants pick projects of pairwise different success probabilities, and the larger the number of entrants, the more radical the most radical project becomes. Generally, entrants tend to choose more radical R&D approaches and are more likely to generate the highest value innovation. Thus, the need of entrants to be acquired yields an entirely new explanation of why radical innovations tend to come from entrants. We illustrate our theoretical findings by a qualitative empirical study of the Electronic Design Automation industry, and derive implications for research and management.

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1. Introduction

Firms differ in their ability to innovate. In particular, as numerous empirical studies found (e.g., Baumol 2004, Scherer and Ross 1990), new entrants to an industry are more likely to create breakthroughs, while incumbent firms are more prone to generate incremental innovations. Why is this, and what does it imply for management strategy? To the extent that the answer lies in myopia and organizational rigidities of established firms (Freeman et al. 1983, Hannan and Freeman 1977, Stinchcombe 1965), management should try and emulate the strengths of new entrants. Internal corporate venturing—enabling entrepreneurship within the corporation—is an important approach in this direction (e.g., Block and MacMillan 1993, Miles and Covin 2002, Sykes and Block 1989). However, if the answer is rather that pursuing incremental innovations is economically rational for incumbents, and aiming at radical innovations optimal for entrants, then the normative implications are entirely different. In this case, external corporate venture capital—the investment in externally originated new ventures (e.g. Dushnitsky and Lenox 2005, Gompers and Lerner 2009, Miles and Covin 2002)—or the outright acquisition of such start-ups may provide solutions. Thus, it is critically important to understand why in a given industry radical innovations come from new entrants, if such is the case.

Various theoretical studies (in particular, Reinganum 1983) have analyzed incumbents' and entrants' economic incentives for innovation, by and large confirming the empirical findings mentioned above. An important distinction is in place, however, with respect to how entrants compete with incumbents. Early models assumed product market competition (Arrow 1962, Gilbert and Newbury 1982, Reinganum 1983). However, a cooperative agreement between an entrant and an incumbent should, in general, be superior, both because of increased market power (e.g., Gans and Stern 2000) and because entrants typically lack the broad resource base of incumbents.

In particular, financing considerations may speak for acquisition rather than product market competition. When conditions for initial public offerings (IPOs) are unattractive, venture capitalists rather rely on trade-sales for liquidating their investments (Giot and Schwienbacher, 2007; Mason, 2007;

Giudici and Paleari, 2003). Furthermore, weak IPO markets decrease the availability of venture capital in the first place (Leleux, 2007), so that young firms that run out of liquidity may directly seek to be acquired. This tendency should be particularly pronounced in industries where new firms can start with modest funding for their R&D, but face strongly increasing financing needs later (e.g., for clinical testing or for building a sales and service network). Arguably, since the burst of the Internet bubble in 2000/2001 IPO conditions have generally been unattractive, especially after the onset of the financial crisis in 2008 (Clarysse et al., 2011), shifting the balance further from IPOs to trade sales. Reflecting this importance, some more recent theoretical studies allow for a successful entrant to be acquired by (or to license its invention to) one incumbent (Gans and Stern 2000; Kleer and Wagner, 2012).

Our paper contributes to this stream of the literature. However, our approach differs in two respects from earlier work. First, we note that in many industries the number of aspiring start-ups is, for each technological innovation, higher than the number of incumbents that could potentially acquire them. If this is the case, and if each incumbent buys at most one start-up for each innovative technology, then the start-ups will compete to be acquired. Second, with the notable exception of Färnstrand Damsgaard et al. (2009), all previous studies choose innovation effort—i.e., budget spent—as the players' choice variable. However, given the limited financial resources of entrants, they are unlikely to outperform incumbents in this dimension. Also, they may not have to: in many industries, among them software and biotechnology, capital requirements in early phases of R&D projects are modest, and so budget spent is not the most relevant lever for radicalness of an innovation. Instead, it appears plausible that entrants distinguish themselves from incumbents by choosing R&D approaches of lower success probability and concomitant higher value in case of success. Thus, entrants may achieve more radical innovations—where "radical" refers to the value of the innovation in case of success—not by spending larger budgets, but by pursuing more novel (and hence riskier) approaches.

In our model, we consider an industry consisting of one incumbent and N entrants. The firms conduct R&D with the aim to develop an innovation at a fixed cost normalized to zero. Only the incumbent can commercialize an innovation, so the entrants' goal is to be acquired. Firms' choice variable is the success probability of their R&D projects, with projects of lower success probability having a higher value in case of success. A "value function" links this value to a project's success probability. In the first stage of the game, firms select their projects; in the second stage, after the outcomes of the projects are realized, the entrants compete for being acquired by the incumbent.

Central results of our analysis are the following. There always exists an equilibrium in which all entrants choose more radical R&D projects than the incumbent—i.e., projects of lower success probability and, in case of success, higher value. In this equilibrium, all entrants choose pairwise different strategies; competition between entrants drives the "radicalness" of their innovation in the sense that a larger number of entrants leads to an increase in the value, in case of success, of the most radical innovation project. In turn, no equilibrium exists in which the incumbent chooses the most radical project. Furthermore, for a specific value function and $N \leq 3$ we show that the equilibrium in which the incumbent chooses the least radical project is unique. We show that our key results do not depend on the timing of R&D decisions, the distribution of bargaining power in the market for acquisitions, and the introduction of more incumbents. We thus obtain the rather robust result that, overall, entrants pursue more radical innovations than the incumbent.

We then illustrate and support our analysis by a qualitative empirical study of the electronic design automation (EDA) industry. This industry, developing software tools for the automated design of computer chips, consists of three large incumbents and numerous start-ups. It features those characteristics that we assume in our model—start-ups that compete in R&D with each other and with incumbents, and that need to be acquired by the latter if they are successful—and shows outcomes that are predicted by our theoretical analysis, in particular, start-ups that go for R&D projects with lower success probability and higher value in case of success. This empirical study confirms that our model is practically relevant.

Our results of entrants originating more radical innovations appear familiar from the literature, yet are based on a fundamentally different mechanism than similar findings in earlier studies. In our model, the fact that entrants produce more radical innovations derives from the assumptions that (a) firms choose innovation projects characterized by success probability (rather than effort), and (b) entrants, if successful, need to be acquired in order to commercialize their innovation. No cannibalization effect (Arrow 1962) or organizational rigidities (Freeman et al. 1983, Hannan and Freeman 1977, Stinchcombe 1965) on the side of the incumbent are assumed. Our model also makes predictions that differ from those of established models—in particular, that entrants choose pairwise distinct strategies and that the expected value of the most successful innovation increases with the number of entrants. More generally, our approach suggests that the existence of a market for technology—whether patents or entrant firms are traded in this market— plays an important role in explaining the above stylized facts in the innovation and entrepreneurship literatures.

The remainder of the paper is structured as follows. In the following section, we review the relevant literature. In Sections 3 to 5, we introduce the model, analyze it, and perform robustness checks. Next, we illustrate this analysis by a qualitative empirical study of the EDA industry. In the final section, we summarize and discuss our findings and conclude.

2. Literature Review

There is broad evidence from a number of high-technology industries that acquisitions of small, innovative target firms frequently pursue the goal of gaining technology access and of preempting technology competition (Bloningen and Taylor 2000, Grimpe and Hussinger 2008a, b, Hall 1990, Lehto and Lehtoranta 2006, Lerner and Merges 1998).[1] In line with our analysis, Grandstrand and Sjölander (1990) show that start-ups' innovation is more radical than that of incumbents, and they suggest a division of scientific labor between entrants and incumbents that establishes their roles as targets and acquirers. This view is supported by Lindholm (1996), who shows that small firms take active steps to increase their odds of being acquired. A weak position in complementary assets on the side of the entrant increases the

[1] It should be noted, though, that Desyllas and Hughes (2008) attribute less importance to innovation-related variables, finding that from a target perspective they contribute little to explaining acquisition by a large firm.

gains from trade of technology, and well-established intellectual property rights and involvement of professional intermediaries are found to increase the likelihood that these gains are realized by the entrant and the incumbent (Gans et al. 2002, Hsu 2006).

R&D competition between entrants and incumbents in the shadow of acquisition (or, technology licensing) was first analyzed theoretically by Gans and Stern (2000). They model in detail the negotiations between an incumbent and an entrant over an innovation and show how the acquisition price depends crucially on the strength of intellectual property protection and on the possibility of the entrant to market the technology. This, in turn, determines the two firms' payoff from and incentives to do R&D. Kleer and Wagner (2012) model competition between small and large firms for an exclusive patent, assuming R&D efficiency advantages for small and exploitation advantages for large firms. Among other things they derive, and confirm empirically, that acquisitions increase overall innovation output. Compared to Gans and Stern (2000), we focus less on the subtleties involved in technology bargaining and assume a simple, competitive market for technology. This allows us to set up a tractable model where the *type* of R&D project chosen by the incumbent and multiple entrants can be analyzed.

Our paper is also related to the well-established literature that studies the choice of the "risk-return" profile of R&D projects, either in terms of the success probability, the variance in the return, or the correlation to competitors' R&D projects. This approach has, for example, been used to study the clustering of firms in geographical and product space (Gerlach et al. 2005, 2009), the efficiency of the portfolio of R&D projects in a competitive market (Bhattacharya and Mookherjee 1986, Dasgupta and Maskin 1987), the optimal selection of R&D projects (Ali et al. 1993, Cabral 1993), and the persistence of market dominance (Cabral 2002). Closest to our setup, Färnstrand Damsgaard et al. (2009) consider the choice of success probability by an entrant and an incumbent firm. They show that if the entrant incurs a higher cost of commercializing an innovation than the incumbent, then this induces the entrant to pursue a more radical R&D project.

3. The Model

We consider an industry consisting of one incumbent firm (I) and $N \geq 1$ entrants. All firms conduct R&D with the aim to develop a product for a new market segment. Only the incumbent can market an innovation, so the entrants' goal is to be acquired by the incumbent.[2] Firms choose an R&D project from a given set of combinations of success probabilities and values in case of success. To keep the analysis tractable and in line with our motivation, we focus on success probability as the only choice variable rather than also including the level of R&D investment. That is, costs are identical for all firms and normalized to zero.

We assume that firm i ($i = I, 1, \ldots, N$) chooses a project characterized by a success probability p_i from [0,1]. A successful project results in an innovation of value $\pi(p_i)$ if it is commercialized by the incumbent. If a project is not successful, its value is zero. We call $\pi(\cdot)$ the "value function" and assume it is differentiable and strictly decreasing. Furthermore, we assume that (i) $p\pi(p)$ is concave and (ii) $p\pi(p)$ takes on a maximum at some $\tilde{p}$, $\tilde{p} \in (0,1)$. For a given set of success probabilities $p_I, p_1, \ldots, p_N$, let Π_i denote player i's expected payoff. Notice that all firms are assumed to have the same R&D possibilities. Hence, if the incumbent and the entrant make different R&D choices, it is not due to intrinsic differences in their R&D capabilities. The expected value of the most valuable innovation, denoted by $E[V_{max}]$, is a function of the N+1 success probabilities chosen by the incumbent and the entrants. We assume that $E[V_{max}]$ is strictly concave such that there exists a unique combination of success probabilities (modulo symmetry among the firms) maximizing $E[V_{max}]$.

We employ the value function of $\pi(p) = 1 - p$ to illustrate our results. This function fulfills the requirements defined above, with $p\,\pi(p)$ and $E[V_{max}]$ being concave, and $p\pi(p)$ assuming its maximum at

[2] If not acquired by the incumbent, the entrants do not have the choice to enter the market and compete with the incumbent as in Rasmusen (1988).

$\widetilde{p} = 0.5$. For this specific case, we can furthermore prove several uniqueness results that are elusive for the general case.

In the main analysis, we assume that all firms take their R&D decisions simultaneously. Upon choice of R&D decisions, Nature moves and R&D outcomes are realized. In the final stage—Stage 2 in the simultaneous game, Stage *N+2* in the sequential game—the incumbent may acquire an entrant. In the acquisition stage, the entrants simultaneously make price offers to the incumbent, which either uses its own project or accepts the best offer.[3] Alternatively, the acquisition can be thought of as involving only the entrant's innovation, not the entire firm. To keep the model solvable, we assume that the acquisition happens in a single step, without staged investments or toehold purchases. Finally—not modeled explicitly—products are sold and profits in the market are realized.

4. Solving the Model

In this subsection, we prove existence of an equilibrium in which the incumbent picks the least radical project, show that this equilibrium is welfare optimal, prove non-existence of equilibria in which the incumbent chooses the most radical project, and for the specific value function of $\pi(p) = 1 - p$ show that the above-mentioned equilibrium is unique. We proceed in three steps. We solve the game backwards by looking at the acquisition stage first. Then, we turn to the R&D choices of the firms. We first look at a

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[3] When the incumbent negotiates with the most successful entrant, its threat point, or (maximum) willingness to pay, is the difference in value between the best and the second best project. This is also the negotiable surplus since the entrant's (minimum) willingness to receive is zero. Our approach to modeling the negotiation allocates all negotiation power to the entrant in the bilateral bargaining in the sense that it can capture the incumbent's willingness to pay completely. Notice that this does not imply that the incumbent is left with no gains from trade: if there is more than one entrant, the competition among the entrants implies the incumbent can appropriate a surplus corresponding to the value of the second best project. More generally, the allocation of the bargaining power is less critical in our framework (as we show formally in Section 5.1) since we do not study entrants' nor incumbent's investments into R&D (as, e.g., Gans and Stern 2000)—which obviously are strongly affected by the surplus sharing rule—but rather their choice of success probabilities.

model with one incumbent and two entrants in order to illustrate the mechanisms of the model and to provide economic intuition for our results. Finally, we generalize our results to more than two entrants.

4.1. The Acquisition Stage

The incumbent acquires one entrant at most, as it can only use the technology of one of the entrants. We denote the value of firm *i*'s realized R&D outcome by π_i, $\pi_i \in \{0, \pi(p_i)\}$.

Lemma 1. *(i) If two or more entrants have higher realized R&D values than the incumbent, then the incumbent acquires the entrant with the highest realized value (j) at a price of* $(\pi_j - \pi_k)$*, where k is the entrant with the second-highest realized value.*

(ii) If only one entrant (j) has a higher realized value than the incumbent, then the incumbent acquires this entrant at a price of $(\pi_j - \pi_I)$*.*

(iii) If no entrant has a higher realized value than the incumbent, then the incumbent makes no acquisition.

Proof: Follows from standard Bertrand competition logic.

4.2. The R&D Stage

4.2.1. One Incumbent and Two Entrants

We start by looking at an industry with two entrants (*N*=2). Assuming without loss of generality that $p_2 \leq p_1$ and using Lemma 1, the profit function of the incumbent is:

$$\Pi_I(p_I) = \begin{cases} p_2 p_1 \pi(p_1) + (1 - p_2 p_1) p_I \pi(p_I) & if \quad p_2 \leq p_1 \leq p_I \\ p_I \pi(p_I) + (1 - p_I) p_2 p_1 \pi(p_1) & if \quad p_2 \leq p_I < p_1 \\ p_I \pi(p_I) + (1 - p_I) p_2 p_1 \pi(p_1) & if \quad p_I < p_2 \leq p_1 \end{cases} \tag{1}$$

If the realized values of the entrants' technologies are higher than the realized value of the incumbent's technology, the entrants are competing to be acquired. Then, the incumbent acquires the entrant with the most valuable technology at a price that secures the incumbent a profit equal to the value of the other entrant's technology. In all other circumstances, the incumbent's profit corresponds to the value of its own technology. This happens either because the incumbent acquires the only entrant with a superior technology at price that leaves the incumbent indifferent between acquisition and no acquisition, or because there is no entrant with a more valuable technology to acquire.

An entrant only makes a profit if it has developed the technology of the highest realized value. It follows from the analysis of the acquisition stage summarized in Lemma 1 that the expected profit of entrant i is Pr[Acquisition] · E[Acquisition price] where:

E[Acquisition price] = $\pi(p_i)$ – E[Value of the second best technology | Acquisition], (2)

Pr[Acquisition] = p_i · Pr[No technology of higher value than $\pi(p_i)$ exists]. (3)

The profit function of entrant i is thus:

$$\Pi_i(p_i) = \begin{cases} (1-p_j)p_i\big(\pi(p_i) - p_I\pi(p_I)\big) & if \quad p_j \leq p_i \leq p_I \\ (1-p_j)(1-p_I)p_i\pi(p_i) & if \quad p_j \leq p_I < p_i \\ p_i\left(\pi(p_i) - p_j\pi(p_j) - (1-p_j)p_I\pi(p_I)\right) & if \quad p_i < p_j \leq p_I \end{cases} \tag{4}$$

We focus on an equilibrium in which $p_2^* \leq p_1^* \leq p_I^*$. The existence of other equilibria is discussed below. Maximizing profits yield the first-order conditions characterizing the equilibrium:

$$\frac{\partial \Pi_I(p_I)}{\partial p_I} = 0 \Leftrightarrow \pi(p_I^*) = -p_I^*\pi'(p_I^*), \tag{5}$$

$$\frac{\partial \Pi_1(p_1)}{\partial p_1} = 0 \Leftrightarrow \pi(p_1^*) - p_I^*\pi(p_I^*) = -p_1^*\pi'(p_1^*), \tag{6}$$

$$\frac{\partial \Pi_2(p_2)}{\partial p_2} = 0 \Leftrightarrow \pi(p_2^*) - \big(p_1^*\pi(p_1^*) + (1-p_1^*)p_I^*\pi(p_I^*)\big) = -p_2^*\pi'(p_2^*). \tag{7}$$

The left-hand side (LHS) of the incumbent's first-order condition (5) is the value of the own technology in case of success, which corresponds to the marginal benefit from increasing the success probability (in circumstances where the value of the incumbent's own technology determines its profit). The right-hand side (RHS) of the same equation represents the marginal cost (in the form of reduced technology value in case of success) of increasing the success probability. The two first-order conditions (6) and (7) characterizing p_1^* and p_2^* can be interpreted in a similar manner. The LHS is the expected acquisition price, which is the marginal benefit from increasing the success probability conditional on an acquisition taking place. The RHS is the reduction in the value of the technology, and thus in the acquisition price, that constitutes the marginal cost of increasing the success probability conditional on acquisition.[4]

The first-order conditions can be solved recursively, and it follows that $p_2^* < p_1^* < p_I^* = \tilde{p}$. We prove below for the more general case of N entrants that these success probabilities constitute an equilibrium, which involves showing for each firm that the profit function has a global maximum at the equilibrium success probability given the R&D choices of the other firms.

As an illustration, consider the value function of $\pi(p) = 1 - p$. This function fulfills the requirements defined above, with $p\pi(p)$ being concave and assuming its maximum at $\tilde{p} = 0.5$. The equilibrium actions for the incumbent and entrants are, respectively, $p_I^* = 0.5$, $p_1^* = 3/8 = 0.375$, and $p_2^* = 39/128 \approx 0.305$. Figure 1 illustrates the firms' payoffs as a function of their success probability given the equilibrium choices of the other firms. Note that the payoff functions are kinked, but continuous, where the focal firm's success probability equals the (equilibrium) value of one of the two other firms (with the exception of $\Pi_I(p)$, which is differentiable at $p = p_2^*$).[5]

4 The first-order condition for entrant 1, Equation (6), has a parallel to the models by Färnstrand Daamsgard et al. (2009) and Haufler et al. (2012). In these models, $[p\pi(p)]'$, evaluated at p_1, needs to be equal to an entry cost, while in our model it needs to equal the expected value of the incumbent's project. The latter can thus be interpreted as a sort of entry hurdle.

5 The kinks in the entrants' profit functions appear for the following reason: once an entrant (1, say) chooses a higher success probability than the other entrant (2), entrant 2 is no longer considered a competitor for entrant 1 at the acquisition stage; an acquisition of 1 only occurs conditional on entrant 2 being unsuccessful. This increases the expected acquisition price and, thus, the marginal benefit from increasing the success probability conditional on acquisition. (The profit function is continuous where the focal entrant's success probability equals the equilibrium success probability of one of the other firms, because the increase in the acquisition price is offset by a decrease in the acquisition probability.) The kink in the incumbent's profit function at $p_I = p_1^*$ is caused by a decrease in the marginal cost of increasing the success probability as it becomes entrant 1's technology, rather than the incumbent's own technology, that determines the price at which entrant 2 is acquired if all R&D projects are successful.

--- Insert Figure 1 about here ---

In this equilibrium all entrants aim for more radical innovations than the incumbent. This finding is in line with observations from the EDA industry as well as with established results from the literature. Note, however, that it is not based on the cannibalization effect as the incumbent is not present initially in the market segment considered. Instead, it derives solely from the fact that the incumbent, but not the entrants, is able to market the innovation at hand. In particular, unlike the entrants, the incumbent also benefits from having the second most valuable technology in the market, as it improves its bargaining position when negotiating with the entrant that developed the project of highest realized value. The entrants, on the other hand, are in a different situation as they only make profits by being acquired if they have developed the highest quality project. This creates a strong incentive for them to pursue a project of high potential value but low success probability in order to have the most valuable technology. The equilibrium outcome where the incumbent pursues a less radical project than all entrants thus reflects the difference in the value of being second best in the market.

Another notable feature of the equilibrium is that the ex-ante symmetric entrants choose asymmetric success probabilities in equilibrium. By choosing a success probability that is sufficiently different from the ones chosen by the other firms in the industry, an entrant avoids the risk of ending up in a situation where it faces tough competition at the acquisition stage from a firm that offers a technology of the same, or a very similar, value. Thus, differentiation in terms of success probability-return choices softens competition in much the same way as differentiation in product space does; see Gerlach et al. (2009) for further discussion of this point.

Turning to the welfare properties of the equilibrium, consider a hypothetical social planner who maximizes total welfare. Since the identity of the firm that develops the most valuable technology does not affect total welfare, the social planner maximizes the expected value of the technology brought to the market:

$$Max_{p_I,p_1,p_2}\{p_2\pi(p_2) + (1-p_2)p_1\pi(p_1) + (1-p_2)(1-p_1)p_I\pi(p_I)\}, \quad (8)$$

which yields the first-order conditions (5) - (7). It follows immediately that the firms' equilibrium R&D choices are welfare-maximizing. Hence, in a market that fits our model assumptions, there is no market failure with respect to the type (i.e., success level) of innovation that firms pursue.[6] The intuition behind this somewhat surprising result has two parts. First, it is optimal from a welfare point of view to have a firm choosing $\tilde{p}$. This firm, if successful, delivers the technology of highest expected value in circumstances where the other, more ambitious R&D projects fail. In the equilibrium considered, this role is played by the incumbent. Second, an entrant only makes a profit if it has the best technology, and its profit is the difference in value relative to the second best technology, see equation (2). This also corresponds to the incremental social value of the project; i.e., the welfare lost if this technology did not exist. Since the profit that an entrant earns from an R&D project is equal to the project's social value, private and social incentives are aligned. Therefore, the entrants make the welfare maximizing R&D decisions. We discuss the robustness of this result in Section 5.3.

4.2.2. One Incumbent and N Entrants

We now turn to the case of *N* entrants. Since most results and intuitions carry over from *N*=2, our focus is here on the additional insights that the general analysis provides. All proofs are in the Appendix.

Lemma 2. *There is no equilibrium in pure strategies in which two or more firms choose the same success probability.*

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6 Regarding the number of firms that enter in a free-entry equilibrium, assuming a fixed cost of entering, welfare optimality depends on the role played by the marginal entrant. If the marginal entrant is the one choosing the lowest success probability, its profit corresponds exactly to the social value that it creates. The equilibrium is then also welfare maximizing in terms of the number of active firms. However, if the expected profit of the marginal entrant is greater than this—for example, equal to the average profit among the entrants—then the equilibrium is characterized by excessive entry.

Having established that firms play asymmetric strategies in equilibrium, we turn to the main analysis. First, re-label the *N+1* firms in such a way that $p_0 \geq \cdots \geq p_N$.

Definition 1. *Set* $h_0=0$, *and define* $\{\bar{p}_0, .., \bar{p}_N\}$ *and* $\{h_1, .., h_{N+1}\}$ *recursively as follows:*

$$h_k := \bar{p}_{k-1}\pi(\bar{p}_{k-1}) + (1 - \bar{p}_{k-1})h_{k-1} \quad \text{for } k = 1,...,N+1 \tag{9}$$

$$\pi(\bar{p}_k) + \bar{p}_k\pi'(\bar{p}_k) := h_k \quad \text{for } k = 0,...,N \tag{10}$$

Notice that h_k equals the expected value of the highest realized value among firms 0, 1,…, *k*–1, and that social welfare is equal to h_{N+1}.

Lemma 3. *The success probabilities* $\{\bar{p}_0, .., \bar{p}_N\}$ *have the following properties:*

(i) $\tilde{p} = \bar{p}_0 > \bar{p}_1 > \cdots > \bar{p}_N$;

(ii) $\{\bar{p}_0, .., \bar{p}_i\}$, $i \leq N$, *maximize the expected value of the best technology among* i+1 *R&D projects. In particular,* $\{\bar{p}_0, .., \bar{p}_N\}$ *maximize social welfare.*

We are now ready to present the main result of the theoretical analysis.

Proposition 1. *(i) There exists an equilibrium in pure strategies in which firms make the welfare maximizing R&D choices. Renumbering the entrants, the incumbent chooses* $p_I^* = \bar{p}_0$ *and entrant k chooses* $p_k^* = \bar{p}_k$, *k = 1,..,N. This is the unique equilibrium (modulo symmetry among the entrants) in which the incumbent chooses the highest success probability.*

(ii) For $N \geq k$ *the equilibrium value of* p_k *is independent of N.*

(iii) Expected payoffs are highest for the incumbent. For the entrants, they decrease with k. That is, $\Pi_I > \Pi_1 > \ldots > \Pi_N$.

Proposition 1 confirms that the results obtained for *N*=2 hold generally. There exist an equilibrium in which the incumbent chooses a higher success probability than all *N* entrants, where the firms choose pair-wise different success probabilities, and where the R&D choices are welfare maximizing.

Proposition 1 allows for comparative statics with respect to the number of entrants. Part (i) and (ii) show that increasing the number of entrants from N to $N+1$ neither changes the R&D choice of the incumbent nor the R&D choices of entrants 1 to N. However, a more radical R&D project with a lower success probability is added by entrant $N+1$ to the industry portfolio of R&D projects. That is, increasing the number of entrants not only leads to a higher probability that some innovator will succeed at all, but also pushes the limit of the highest attainable innovation value.

The finding that the incumbent does not change its R&D choice in the face of market entry contrasts in an interesting way with results by Gans and Stern (2000), who show that an incumbent behaves differently (invests less) in the face of entry—anticipating the opportunity to acquire a successful entrant—than as a monopolist.

As the competition among entrants intensifies, the entrants are pushed to pursue increasingly radical R&D projects to mitigate competition. Still, part (iii) of the proposition shows that these more radical projects are less profitable in expectation. If there is a fixed cost, e.g., of doing R&D for the entrants, there would, thus, be a limit to the number of firms that the market can support.

Proposition 1 is in line with the empirical observation that entrants tend to pursue innovation projects of lower success probability but higher value in case of success than incumbents. This result would be moot if also equilibria with any other order of success probability levels existed, in particular with the incumbent choosing the highest-risk project ($p_1 > \ldots > p_N > p_I$). The following proposition shows that the latter type of equilibrium can be excluded.

Proposition 2. *There is no equilibrium in pure strategies in which the incumbent chooses a project with lower success probability than all entrants.*

The logical next step would be to formulate and prove a proposition about existence or non-existence of equilibria in which the incumbent chooses some intermediate risk level, that is, with $p_1 > \ldots > p_I > \ldots > p_N$. We conjecture that no such equilibria exist, but we can not prove it in full generality. However, we can prove the statement for the specific value function introduced above, $\pi(p) = 1 - p$, and for the cases of N=2, N=3.

Proposition 3. *Let the value function be given by $\pi(p) = 1 - p$. Then, (i) for N=2 there is no equilibrium in pure strategies in which $p_1 > p_I > p_2$. The unique equilibrium is characterized by $p_I = 0.5$, $p_1 = 0.375$, and $p_2 \approx 0.305$.*

(ii) For N=3 there is no equilibrium in pure strategies in which $p_1 > p_I > p_2 > p_3$, and no equilibrium in which $p_1 > p_2 > p_I > p_3$. The unique equilibrium is characterized by $p_I = 0.5$, $p_1 = 0.375$, $p_2 \approx 0.305$, and $p_3 \approx 0.274$.

Proposition 2 establishes, for the case of general $\pi(p)$ and N, that in equilibrium the incumbent never chooses the highest-risk project. For the specific case of $\pi(p) = 1 - p$ and $N \leq 3$, Proposition 3 shows that the incumbent always chooses the project with lowest risk. Overall, thus, the mere definition of entrants as firms that need to be acquired in order to commercialize their innovation generates the result that entrants focus on riskier, but in case of success more valuable or more radical projects.

5. Robustness Checks

In this section, we consider different variations of the model in order to explore the robustness of the results obtained and to identify the key assumptions of the model. It is assumed throughout that N=2.

5.1. Generalized Bargaining Game

Consider a bargaining game at the acquisition stage where a take-it-or-leave-it offer is made, with probability b, by the incumbent rather than the entrants. Notice that this bargaining game encompasses the one considered in our main model as a special case (b = 0), but allows for a more equal distribution of bargaining power between the incumbent and the entrants.

Proposition 4. *Suppose, for N=2, that the incumbent makes a take-it-or-leave-it offer to the entrants with probability b, $0 \leq b \leq 1$, and the entrants make competing offers to the incumbent with the complementary* *probability. Then, there exists an equilibrium in pure strategies in which the success probabilities chosen by the firms are identical to those described in Proposition 1.*

Proposition 4 confirms that the different R&D choices of the incumbent and the entrants are driven by the difference in the value of having the second best technology rather than the specific form of the bargaining game.

5.2. Two Incumbents and One Entrant

In our main model, there is one incumbent that controls access to the market. The following proposition shows that our qualitative results are robust to an increase in the number of firms with access to the market.

Proposition 5. *Suppose that there are two incumbents and one entrant. Then, there exists a unique equilibrium in pure strategies in which the firms choose the success probabilities described in Proposition 1. In this equilibrium, the entrant chooses the lowest success probability ($\bar{p}_2$) and the incumbents choose the higher success probabilities ($\bar{p}_0$ and $\bar{p}_1$).*

When there are two incumbents, the incumbents choose different success probabilities in equilibrium in order to avoid competing all profits away, either in the product market (if the entrant is unsuccessful) or in the acquisition market (if the entrant is successful). More importantly, Proposition 5 shows that the entrant chooses a more radical project than the incumbents. This reflects again the value for the incumbents of having the second best technology, which induces them to go for less radical projects than the entrant who needs to have the best technology to make profits. Notice also that our results are slightly stronger in the case of two incumbents and one entrant as we are able to show uniqueness of the equilibrium for the general function $\pi(p)$.

Finally, it can be shown that if all three firms are incumbents, the only equilibrium in pure strategies is one where the firms play $\bar{p}_0$, $\bar{p}_1$, and $\bar{p}_2$. The incentive of the firms to differentiate themselves in terms of success probability-return exists thus independently of how many firms have market access. However, our analysis shows that if there are entrants and incumbents, the entrants tend to be the ones pursuing the more radical innovation projects in equilibrium.

5.3. Sequential Moves

Real-world R&D decisions are often best modeled as simultaneous moves as done above, since it is plausible that firms have to make irreversible R&D decisions before observing their competitors' choices. Notwithstanding this, there may exist situations in which firms discover market opportunities at rather different points in time such that the R&D choices of early movers become observable to followers before the latter make their own R&D decisions. In the analysis of the sequential-move game, we restrict ourselves to N=2. First, a game is analyzed where the incumbent moves first, then entrant 1, and finally entrant 2. A general value function is assumed here. Afterward, we consider all possible orders of moves for the value function $\pi(p) = 1 - p$. All proofs of the results in this subsection are available from the authors upon request.

Turning to the first part of the analysis, the following lemma describes the equilibria of the subgames starting after the incumbent has chosen its success probability.

Lemma 4. *Consider the Nash equilibria of the subgames starting after the incumbent has chosen p_I. Then, (i) entrant 1 chooses the success probability that maximizes the welfare resulting from the innovations of the incumbent and of entrant 1 conditional on p_I; (ii) entrant 2 chooses the success probability that maximizes the welfare resulting from the innovations of all firms conditional on p_I and p_1.*

The profit of entrant 2 coincides with the social value of its innovation, as discussed above, which leads it to take the welfare maximizing R&D decision. Entrant 1 has to consider the reaction of entrant 2 when deciding on its R&D project. It is optimal for entrant 1 to choose a profitable R&D project with high success probability, and it foresees that entrant 2 will choose a more radical R&D project with lower success probability. Hence, entrant 1 will only make a profit if entrant 2 fails. Ideally, entrant 1 would like to pick a project that maximizes entrant 1's expected profit when entrant 2 fails and that minimizes the success probability that entrant 2 chooses. It turns out that there is no conflict between these two objectives. By choosing the welfare maximizing success probability conditional on p_I, entrant 1 maximizes its expected profit when entrant 2 fails and maximizes the competitive pressure that entrant 2 experiences, thereby pushing entrant 2 to choose a more radical R&D project with a low success probability.

We define the success probabilities $\hat{p}_1$ and $\hat{p}_2$ by $\hat{p}_1\pi'(\hat{p}_1)+\pi(\hat{p}_1)=p_I\pi(p_I)$ and $\hat{p}_2\pi'(\hat{p}_2)+\pi(\hat{p}_2)=\hat{p}_1\pi(\hat{p}_1)+(1-\hat{p}_1)p_I\pi(p_I)$, respectively. Furthermore, we define $\overline{p}_I$ implicitly by $p_I\pi(p_I)+(1-p_I)\tilde{p}\pi(\tilde{p})=\hat{p}_1\pi(\hat{p}_1)+(1-\hat{p}_1)p_I\pi(p_I)$. With these definitions, we can put down:

Proposition 6. *The equilibrium success probabilities of the sequential-move game with the order of moves given by I, 1, 2 coincide with those of the simultaneous-move game if the following condition holds for all* $p_I \le \overline{p}_I$*:*

$$\left.\frac{d^2\left(p\pi(p)\right)}{dp^2}\right|_{p=\hat{p}_2} \le -\frac{\left(1-\hat{p}_1\right)\left(\pi(\hat{p}_1)-p_I\pi(p_I)\right)}{1-\hat{p}_2}.$$

Expressed verbally, the condition requires that the function $p\pi(p)$ is sufficiently concave. For $\pi(p) = 1 - p$, e.g., it is fulfilled. The intuition behind Proposition 6 is the following. When choosing the success probability of its R&D project, the incumbent faces a trade-off. On the positive side, $p_I = \tilde{p}$ maximizes the expected profit of the incumbent when one or none of the entrants succeed in developing an innovation, because the incumbent earns $p_I\pi(p_I)$ in these circumstances. At the same time, however, $p_I = \tilde{p}$ maximizes the competitive pressure that the entrants face, and so minimizes the best response success probabilities of the entrants as well as the surplus that the incumbent can extract from the entrants' R&D activities. For both (counteracting) effects, the first-order condition is fulfilled at $p_I = \tilde{p}$. One can show that, if the condition in Proposition 6 is fulfilled, the direct effect of p_I on the value of the incumbent's R&D project dominates the indirect effect on the entrants' R&D choices, such that the solution $p_I = \tilde{p}$ to the first-order condition indeed corresponds to a maximum.

In the derivation of Proposition 6, we have assumed that the players are forward looking, following the logic of subgame perfection. Due to the recursive construction of the Nash equilibrium of the simultaneous-move game, myopic firms (i.e., firms that do not consider the effect of their choice on firms moving later in the game) would choose the same success probabilities in the sequential-move game as when moves are simultaneous. Furthermore, one can show that for a game in which the incumbent moves first and then all entrants move simultaneously Proposition 6 holds accordingly.

For the case that not the incumbent, but one of the entrants moves first, one might expect that this firm moves closer to $\tilde{p}$ (which maximizes the expected project value). It might even pick a less radical project than the incumbent. Surprisingly, however, this does not seem to be the case. For N=1 and a general profit function, the incumbent picks $\tilde{p}$ irrespective of the order of moves since its expected profit, $p_I \cdot \pi(p_I)$, is independent of p_1. Hence, the entrant will pick its best response to $p_I = \tilde{p}$ even if it moves first. While a general proof is elusive, numerical simulations for $\pi(p) = 1 - p$, N=2, show robustness of the simultaneous-move outcome when players move sequentially:

Numerical Result 1. *Let the value function be given by $\pi(p) = 1 - p$ and let N=2. Then, the players' equilibrium actions in a sequential game are identical to those in the simultaneous-move game, irrespective of the order of moves. That is, $p_I = 0.5$, $p_1 = 3/8 = 0.375$, $p_2 = 39/128 = 0.3046875$.*

Within the numerical precision of 1e-8, the values of p_I, p_1, and p_2 that were determined in the respective final round of iterations are identical to those stated in Numerical Result 1, no matter if the incumbent moves second or third (the case of I moving first is covered by Proposition 6).[7]

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[7] For each order of moves, we numerically determine the approximate equilibrium values with eight different sets of starting values. In the first set, each variable varies between 0.01 and 0.99; in the later sets, these intervals are successively reduced in

Notice that the analyses in this subsection point to a first-mover advantage for entrants. Given that the firms pick the same R&D projects as in the simultaneous-move game, Proposition 1 shows that entrant 1 earns higher expected profits than entrant 2.

5.4. The Importance of Competition in the Market for Acquisitions

The fact that the acquisition price of an entrant depends on the difference in value to the second best technology is clearly essential for our results as it drives both the entrants' incentive to choose a radical project to push up the acquisition price and the incumbent's incentive to choose a project with a high expected value to minimize the acquisition price.

To illustrate the importance of this assumption, consider a simple variation of the model where the successful firms are equally likely to be granted an exclusive patent that prevents the other firms from marketing their technologies. This removes competition at the acquisition stage as maximally one technology can be marketed.

Using Lemma 1, the expected profit of firm *i* can then be written as:

$$\Pi_i(p_i) = p_i\left(\frac{p_j\, p_k}{3} + \frac{p_j\,(1-p_k)+(1-p_j)p_k}{2} + (1-p_j)(1-p_k)\right)\pi(p_i), \qquad (11)$$

where $i, j, k \in \{I, 1, 2\}$ and $i \neq j \neq k$. It follows immediately that there exists a unique and symmetric equilibrium in pure strategies in which $p_I^* = p_1^* = p_2^* = \tilde{p}$. Unlike the traditional patent race literature that envisions firms competing for one patent, our results rely thus on the assumption that competing technologies can co-exist and compete in the market. In many instances, this assumption is clearly more plausible than that of the patent race winner obtaining a monopoly.

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order to zoom in on the equilibrium values, with interval widths of 1.5e-6 in the final set. For each set, each of the three variables (p_1, p_2, p_I) takes on 1,000 equidistant values. The inner loop of the 10^9 iterations per set yields the best response of the last mover to the choices made by the first and the second mover; the middle loop, the best response of the second mover to the choice made by the first mover, taking the last mover's reaction into account; and the outer loop, the first mover's best strategy, taking the other players' reactions into account. A detailed account of the numerical analysis is available from the authors upon request.

5.5. R&D Investment as the Decision Variable

The choice variable that has been most frequently used in analyses of R&D competition is R&D investment. For the purpose of comparison, let us consider a variant of the model where R&D investment rather than R&D success probability is the choice variable.

In order to formalize this notion, we assume that firm i chooses an R&D intensity ϕ_i, which results in an innovation of value $\pi(\phi_i)$ and 0 with probability $p(\phi_i)$ and $1 - p(\phi_i)$, respectively, $i = 1, 2, I$. The corresponding R&D cost is represented by an increasing and convex function $c(\phi_i)$. Additional R&D investment increases the success probability and/or the value of an innovation. That is, $p'(\phi_i) \geq 0$ and $\pi'(\phi_i) \geq 0$ with at least one strict inequality (notice that firms cannot trade off success probability against value). We make a few additional concavity assumptions, which are specified in the proof of Proposition 7.

Proposition 7. *Suppose that the firms choose the level of R&D investment. Then, there exists a unique equilibrium in pure strategies in which the firms choose pairwise different investment levels and in which the incumbent invests more than the entrants.*

In industries in which the key choice variable is R&D investment, our model thus predicts that the most valuable technologies come from incumbent firms. The incumbent invests more than the entrants, which translates into a higher success rate and a more valuable technology in case of success.[8] The reason why there does not exist an equilibrium in which an entrant invests more than the incumbent is again related to value of having the second best technology: Since the incumbent benefits from its technology both when it is best and second best, it has a stronger incentive to invest in R&D than an entrant who only benefits from its technology when it is the best one.

8 More precisely, it translates into a success rate and a technology value in case of success that are at least as good as those of the entrants, and at least one of them (success rate, technology value) is strictly better than those of the entrants.

The results in Propositions 1 and 7 contrast in an interesting way and illustrate the challenges involved in testing empirically whether incumbents or entrants do the most radical R&D. Indeed, our analysis shows that the answer to this question may depend on something as subtle as the key R&D decision variable in the industry (more generally, on the interplay of R&D investment, success probability, and possibly further choice variables) and that not controlling for this variable may bias results. Regarding welfare, one can show that the investment choices are welfare maximizing if and only if investment into R&D only increases the value of the technology (but not the success probability). In general, however, the incumbent puts greater weight on its own technology than a hypothetical social planner would do, because it is not able appropriate the full value of the entrants' technologies. This results in an equilibrium where the incumbent invests too much and the entrants invest too little from a welfare perspective.

6. Innovation and Acquisition in the EDA Industry

6.1. Industry Background

The EDA industry is a sub-segment of the semiconductor industry, providing tools that support the (automated) design of integrated circuits.[9] Historically hardware-based involving dedicated workstations for computer-aided design, it evolved into a software-based industry in the 1980s. EDA firms provide a large set of tools to aid chip designers in transforming an abstract logical representation of an integrated circuit into a structure that can be manufactured physically. These tools cover a complex process from chip design to testing. It can be subdivided in a number of subprocesses, each focused on one special aspect of design and design testing. The EDA industry is characterized by high industry concentration with 68% of the 2009 revenues being generated by the largest three firms (Solid State Technology 2010) and by a larger number of small firms entering the industry every year that ultimately either are acquired

[9] A brief description of innovation in the EDA industry is also contained in Kleer and Wagner (2012).

by one of three large incumbents or go out of business. The number of start-ups and young firms has risen continuously to over 400 firms in 2005 (Desai 2005; Solid State Technology 2010; iSuppli 2010). Industry turnover was more than $4 billion (bn) in 2009 (compared to this total revenue of chip manufacturers was $230 bn).. The industry has until 2006 grown on average 3% year on year whilst growth has slowed somewhat after that, leading to a decline of 4.5% from 2008 to 2009 (Solid State Technology 2010).

6.2. Interviews

Our qualitative empirical study is based on semi-structured interviews with industry experts and larger EDA companies. This approach has been applied in similar exploratory research settings and is also advocated methodologically (e.g., Miles and Huberman 1994). Through our interviews, we study whether or not start-ups, in particular those that are later acquired by large incumbent firms, pursue more radical innovations than incumbents. The questions in the interview guideline are partly derived from extant literature (Henderson 1993, Christensen and Bower 1996) and are partly based on our own knowledge of the industry and the phenomenon under study. In the interviews, we put a particular emphasis on entrants' and incumbents' relative innovation performance, the drivers of performance differentials, facts and figures regarding acquisitions of entrants by incumbents, and the reasons for these acquisitions, in particular those related to innovation. The interview guideline was adjusted as the research progressed to maximize the insights gained from the interviews. From December 2005 until January 2008, eight interviews with 10 interviewees were carried out with senior professionals and scientists who have detailed knowledge of the EDA industry. The list of interviewees comprises representatives from the two largest and from some smaller EDA firms, industry consultants, as well as academics from America and Europe. Each interview lasted between half an hour and two hours. Three interviews were carried out over the phone or by email, all others in person. Interviews were subsequently transcribed and the written material was then analyzed. Two interviews were conducted in German, so that interview quotes were translated to English.[10]

6.3. Drivers of Innovation in the EDA Industry

In the EDA industry, new requirements for innovation and improvement of technological products emerge on a regular basis. This need, identified from the interviews, is driven by two essential factors: the International Technology Roadmap for Semiconductors (ITRS) and the cumulative nature of technological change paired with the highly cyclical nature of the semiconductor industry (Levy 1994). For example, during the most severe downturn in 2000 to 2001, R&D expenditure in the industry significantly dropped and so far has not fully recovered. Semiconductor firms try to mitigate this reduction by strongly pushing suppliers, including those of EDA tools, to innovate in order to reduce cost. As a first stylized fact of the analysis, we put down that there are continuously increasing requirements for EDA tools and hence a permanent demand for innovation in the EDA industry.

6.4. Sources of Innovation in the EDA Industry

Each emerging innovation need in the EDA industry is usually addressed by several start-ups and the incumbents, which in parallel try to develop a solution to these needs. However, as we learned from our interviews, it turns out that incumbents often fail to address these in a systematic manner, as is illustrated in the following statement: *"An example here is in logic simulation. Synopsys, Cadence, and Mentor [the three largest firms in the EDA industry] all acquired their current generation of simulators to replace their existing products. In all cases, smaller companies came up with better algorithms that made their simulators significantly faster than those of the large companies. In all cases, the larger companies tried to compete by creating new simulators themselves prior to making their respective acquisitions, but failed."* Hence, with incumbents failing to innovate successfully, opportunities emerge for start-ups with

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[10] Further details of each interview (date, duration, function of the interviewee, type of organization that he or she is working with) are available from the authors upon request.

better performing products. According to our interviewees, and illustrated by the quote above, these start-ups are frequently acquired by the larger incumbents. Such acquisitions, in turn, can trigger heightened acquisition efforts by competing incumbents to catch up.

As we argue below, the relative success of start-ups compared to incumbents derives partly from the fact that, unrestrained by existing customers and existing products, start-ups are free to pursue more radical innovations. This freedom attracts talented engineers, which in turn further increases the odds of start-ups to prevail in the competition with incumbents: "*It usually remains only a small number of people that create the fundamental technological difference. While these people certainly can be hired by large EDA companies … these people … go and start a new company. This starves the larger company of the knowledge and talent while promoting the potential success of the new venture.*"

As a stylized fact, we note that both, entrants and incumbents innovate, but that incumbents often fail in developing a solution of satisfactory quality—or any solution at all—and in this case usually acquire start-ups.

6.5. The Fate of Entrants in the EDA Industry

The increasingly complex combination of different tools used for chip design (the "design flow") makes it increasingly likely for entrants to be acquired and become integrated into the design flow of one of the three large vendors, as succinctly described in one interview: *"It [acquisition] is getting more common because the tools are getting more complex. … You need more of a 'solution' nowadays. You can't just come out with one point tool, you need to come out and have at least a solution to a subsegment of the problem."*

Hence, it seems that entrants can succeed in the long run only if they are acquired. Our interviews support this conjecture, indicating that if acquisitions are not the only way to survival, they are certainly the most prevalent one. This is partly because being acquired is financially attractive to start-ups since initial public offerings (IPOs) are less predictable and since venture capitalists aiming for a profitable exit always consider the option of a trade sale. Several interviewees confirmed this view, stating that "*most of* *these small companies' dream is to be bought by somebody big*" and "*the success path is to be acquired by a big company*."

Next to these push factors, a number of pull factors were also identified in the interviews. One interviewee pointed out the important role of complementary assets such as a strong international sales force: *"… with their sales network which of course then [after acquisition] explodes compared with the small firm, because they [large incumbents] are already everywhere in Asia, Europe, and elsewhere and they get just another product to sell. And they get worldwide sales support when they need it. … They [small firms] eventually break down because of a lacking sales network and demand for application services which they cannot provide anymore with their own human resources.*" Even more to the point, one entrepreneur stated: "*The goal is always to be acquired. […] The more successful we are, the more urgent it becomes to be acquired.*"

One interviewee described how incumbents exploit the innovative activity of start-ups, in his statement capturing the central message of our model: "*The vast majority of start-ups in EDA fail, as they do in most industries. In some sense, this encourages big companies to only look outside to acquire new technologies—it's cheaper to let the cash efficient start-ups figure out how to design the product and build the market, suffering real failures in many cases, than it is to do it inside the large company.*" In sum, we can put down as a stylized fact that a large share of successful entrants in the industry are—almost always need to be—acquired, and that incumbents rely to some extent on this source of new technology.

6.6. Type of Innovation Pursued

It emerges from the interviews that entrants generally choose riskier innovation projects. Interviewees suggested a number of reasons for this fact. Partly these relate to the obstacles identified in the literature on disruptive innovation (Christensen and Bower 1996, Christensen 1997), namely, that incumbents are often forced to focus on large existing customers: *"So they [large incumbents] are relying on start-ups,* *which then are starting from scratch … so they can apply very new methodology with very new techniques without being restrained by all [existing] customers or all the methodology*."

At the same time, the nexus of new knowledge in the industry often resides in the small start-ups, as the following statement clearly illustrates: "*The current way is that the know-how, the innovation in terms of software, is mostly generated in small firms… The share of employees who in the larger EDA firms are really innovative should be small*."

Fitting with these statements is the observations that large incumbents generally have a weak track record in developing new technologies in-house, but that they are rather successful in developing an existing project further, i.e., at carrying out incremental innovation. At closer inspection, what becomes clear is that not only much of the innovation in the EDA industry emerges out of start-ups but also that in terms of quality, small firms pursue more radical innovation projects—a characteristic that is negatively correlated to the level of probability of success for a project. This view has been confirmed by several interviewees, stating, e.g., *"… but there [in small firms] … has to be a radical core, I would say, otherwise it is not possible"* and *"… the radical stuff is always done by the start-ups."* Hence as a stylized fact, entrants pursue more radical innovation projects than incumbents. That is, they pursue innovation projects that are both more likely to fail and, in case of success, be more valuable than those pursued by incumbents.

Overall, the EDA industry fits both the assumptions made in our model and the key predictions derived from it rather well, thus lending empirical support to our theoretical analysis.

7. Discussion and Conclusion

New entrants to a market are characterized by various features, among them organizational flexibility, the lack of established customer relationships, and the absence of existing products. All of these features contribute to explaining why innovations, in particular radical innovations, are more likely to come from start-ups than from incumbents. Yet, one important explanation for this fact is missing in the list above. Defining entrants solely by the feature that they need to be acquired in order to commercialize their innovations, our model generates—based on an entirely different mechanism than earlier studies—the familiar result that entrants are more likely to produce radical innovations. More precisely, since firms are modeled to choose not research investment but rather the success probability of their innovation project, we find that the incumbent aims at more certain innovations of lower value, while entrants pursue projects that are less likely to succeed but, in case of success, will be more valuable. Furthermore, the more start-ups there are and the stronger the competition between them, the more valuable becomes the most radical project pursued. Also, entrants pick projects of pairwise different success probabilities—a prediction of our model that differs from those of existing ones.

The qualitative empirical study of the EDA industry confirmed that our model assumptions can be realistic. The EDA industry is characterized by few incumbents and numerous start-ups. Both incumbents and start-ups perform R&D, but the latter, by and large, need to be acquired in order to survive in the long run. However, for each type of technology, an incumbent would—with some simplification—only acquire one start-up, so those developing similar technology compete to be acquired. While some of the existing explanations for entrants being superior in developing radical innovations also seem to play a role in the EDA industry, the fact that innovation for start-ups has the character of a contest with acquisition as the prize clearly contributes to the pursuit of radical innovation by start-ups.

Although our empirical study was focused on this one industry, the applicability of our theoretical results is broader. First, several other software-based industries are similar to EDA in that large incumbents provide system products, and therefore we expect our results to also hold in such industries. Second, Cabral (2003) cites evidence from the biotechnology industry where one of the two winners in the race for artificial human insulin was acquired. He also shows that contestants chose approaches differing in terms of their radicality, rather than their effort levels. Related to this, a study by Behnke and Hültenschmidt (2007) found that for the biotechnology industry, trade sales have become more frequent in recent years compared to IPOs; furthermore, even after an IPO a firm may be acquired. Jointly, these aspects suggest that the biotechnology industry is increasingly characterized by features similar to those identified for EDA.

As always, our analysis builds on simplifying assumptions and has limitations that need to be considered when applying the results. First, we explored the robustness of the equilibrium in various ways, but we were not able to demonstrate the uniqueness of the equilibrium in full generality. Second, we did provide a robustness check regarding the number of incumbents in Section 5.2 (with two incumbents and one entrant) but do not address the general case of several incumbents and entrants, as found in the EDA industry. We conjecture that our main result—the entrants picking more radical projects—remains robust, since it relies on the entrants' need to be acquired rather than on the number of acquirers. Furthermore, we conjecture that, if the number of entrants exceeds that of incumbents, the radicalness of the most radical project increases with the number of entrants, since it is based on competition between the entrants. Third, we made the simplifying assumption that entrants need to be acquired in order to commercialize their innovations. In reality, even in industries such as EDA it cannot be fully excluded that some entrant is successful on its own in the long run. However, when the probability of such an event is small enough, our model should be a good approximation. Fourth and finally, we only consider acquisitions in one step rather than staged investments resulting, e.g., from corporate venture capital (CVC) activities. However, Maula and Murray (2000) find acquisitions subsequent to a CVC engagement by the same firm to be extremely rare. In any case, though, our results should be robust to such a generalization: when the incumbent owns a share s in the entrant with the best realized project, then its willingness to pay for this firm would still be the difference in value to the second best project, and it would end up paying this difference for the remaining share, $(1-s)$.

Our study has a number of implications for managers. In industries where our model is applicable, incumbents benefit from a larger number of entrants not only by a lower expected acquisition price but also by an increase in the expected quality of the focal innovation. Accordingly, they might want to support entry and competition among entrants even more, e.g., by making relevant intellectual property accessible (e.g., interface specifications in the field of software, or patents covering specific tests in the field of biotechnology). Furthermore, both incumbents and entrants should assess early on if and to what extent entrants must rely on being acquired, and should adjust their strategies accordingly. For entrepreneurs, our analysis points to a new variant of the well-known first-mover advantage. If an entrepreneur is able to move first, pursue an R&D project of high expected value, and communicate this (credibly) to the market, e.g., through its hiring decisions, other entrepreneurs pick more radical but less attractive R&D projects with a lower probability of success. This reduces the competition that the entrepreneur faces when selling the firm (or the technology) and increases profit.

Market dynamics are multifaceted, in particular the interplay between incumbents and new entrants. With its focus on success probability as a choice variable, entrants' need to be acquired, and competition between a large number of entrants we believe that our study has contributed important new aspects to this variegated picture.

References

Ali, A., M. U. Kalwani, D. Kovenock. 1993. Selecting product development projects: Pioneering versus incremental innovation strategies. *Management Sci.* **39**(3) 255–274.

Arrow, K. J. 1962. Economic welfare and the allocation of resources for invention. R. Nelson, ed. *The Rate and Direction of Inventive Activity.* Princeton University Press, Princeton, NJ, 165–180.

Baumol, W. J. 2004. Entrepreneurial enterprises, large established firms and other components of the free-market growth machine. *Small Bus. Econom.* **23**(1) 9–21.

Behnke, N., N. Hültenschmidt. 2007. New path to profits in biotech: Taking the acquisition exit. *J. Commercial Biotechnology* **13**(2) 78–85.

Bhattacharya, S., D. Mookherjee. 1986. Portfolio choice in research and development. *RAND J. Econom.* **17** 594–606.

Block, Z., I. C. MacMillan. 1993. *Corporate Venturing—Creating New Business within the Firm.* Harvard Business School Press: Boston, MA.

Bloningen, B. A., C. T. Taylor. 2000. R&D intensity and acquisitions in high technology industries: Evidence from the US electronic and electrical equipment industries. *J. Indust. Econom.* **68**(1) 47–70.

Cabral, L. 1993. Bias in market R&D portfolios. *Internat. J. Indust. Organ.* **12** 533–547.

Cabral, L. 2002. Increasing dominance with no efficiency effect. *J. Econom. Theory* **102**(2) 471–479.

Cabral, L. 2003. R&D competition when firms choose variance. *J. Econom. Management Strategy* **12** 139–150.

Christensen, C. 1997. *The Innovator's Dilemma*. Harvard Business School Press: Boston, MA.

Christensen, C. M., J. L. Bower. 1996. Customer power, strategic investment, and the failure of leading firms. *Strategic Management J.* **17** 197–218.

Clarysse, B., A. Bobelyn, I. del Palacio Aguirre. 2012. Learning from own and others' previous experience: The contribution of the venture capital firm to the likelihood of a portfolio company's trade sale. *Small Business Economics*, in press.

Dasgupta, P., E. Maskin. 1987. The simple economics of research portfolios. *Econom. J.* **97** 581–595.

Desai, S. K. 2005. EDA Innovation through Merger and Acquisitions, accessed 14 June 2011 at http://www.edacafe.com.

Desyllas, P. A. Hughes. 2008. Sourcing technological knowledge through corporate acquisition: Evidence from an international sample of high technology firms. *J. High Tech. Management Res.* **18**(2) 157–172.

Dushnitsky, G., M. J. Lenox. 2005. When do firms undertake R&D by investing in new ventures? *Strat. Mgmt. J.* **26** 947–965.

Färnstrand Damsgaard, E., P.-J. Norbäck, L. Persson, H. Vasconcelos. 2009. When do independent innovators make the break-through inventions? Working paper, Research Institute of Industrial Economics, Stockholm, Sweden.

Freeman, J., G. R. Carroll, M. T. Hannan. 1983. The liability of newness: Age dependence in organizational death rates. *Amer. Sociological Rev.* **48** 692–710.

Gans, J., D. H. Hsu, S. Stern. 2002. When does start-up innovation spur the gale of creative destruction? *RAND J. Econom.* **33**(4) 571–586.

Gans, J., S. Stern. 2000. Incumbency and R&D incentives: Licensing the gale of creative destruction. *J. Econom. Management Strategy* **9**(4) 485–511.

Gerlach, H. A., T. Rønde, K. O. Stahl. 2005. Project choice and risk in R&D. *J. Indust. Econom.* **53**(1) 53–81.

Gerlach, H. A., T. Rønde, K. O. Stahl. 2009. Labor pooling in R&D intensive industries. *J. Urban Econom.* **65**(1) 99–111.

Gilbert, R. J., D. M. G. Newbury. 1982. Preemptive patenting and the persistence of monopoly. *Amer. Econom. Rev.* **72**(3) 514–526.

Giot, P., A. Schwienbacher. 2007. IPOs, trade sales and liquidations: Modelling venture capital exits using survival analysis. *Journal of Banking and Finance* **31** 679–702.

Giudici, G., S. Paleari. 2003. R&D Financing and Stock Markets. In M. Calderini, P. Garrone, M. Sobrero (eds.), *Corporate Governance, Market Structure and Innovation*: 217-242. Cheltenham: Edward Elgar.

Gompers, P. A., J. Lerner. 2000. The determinants of corporate venture capital success: Organizational structure, incentives, and complementarities. R. Morck, ed. *Concentrated Corporate Ownership*. University of Chicago Press: Chicago, IL, 17-50.

Grandstrand, O., S. Sjolander. 1990. The acquisition of technology and small firms by large firms. *J. Econom. Behav. Organ.* **13** 367–386.

Grimpe, C., K. Hussinge. 2008a. Market and technology access through firm acquisitions: Beyond one size fits all. Discussion paper no. 08-037. Center for European Economic Research (ZEW), Mannheim, Germany.

Grimpe, C., K. Hussinger. 2008b. Pre-empting technology competition through firm acquisitions. *Econom. Letters* **100** 189–191.

Hall, B. H. 1990. The impact of corporate restructuring on industrial research and development. *Brookings Papers Econom. Activity* **3** 5–135.

Hannan, M. T., J. Freeman. 1977. The population ecology of organizations. *Amer. J. Sociology* **82** 929–964.

Haufler, A., P.-J. Norbäck, L. Persson. 2012. Entrepreneurial innovations and taxation. Working paper No. 896, Research Institute of Industrial Economics, Stockholm, Sweden.

Henderson, R. 1993. Underinvestment and incompetence as responses to radical innovation: Evidence from the photolithographic alignment equipment industry. *RAND J. Econom.* **24**(2) 248–270.

Hsu, D. H. 2006. Venture capitalists and cooperative start-up commercialization strategy. *Management Sci.* **52**(2) 204–219.

iSuppli Corporation. 2010. Semiconductor industry rankings for 2009, accessed 3 January 2013 at http://i.cmpnet.com/pldesignline/2010/03/100317_isuppli_top25.jpg.

Kleer, R., M. Wagner. 2012. Acquisition through innovation tournaments in high-tech industries: a comparative perspective. *Econ. Innovat. New. Tech.*, doi: 10.1080/10438599.2012.703487.

Lehto, E., O. Lehtoranta. 2006. How do innovations affect mergers and acquisitions: Evidence from Finland. *J. Indust. Competition Trade* **6**(1) 5–25.

Leleux, B. 2007. The performance of venture capital investments. In H. Landström (ed.), *Handbook of Research on Venture Capital*: 236-252. Cheltenham: Edward Elgar.

Lerner, J., R. Merges. 1998. The control of technology alliances: An empirical analysis of the biotechnology industry. *J. Indust. Econom.* **46**(2) 121–156.

Levy, D. 1994. Chaos theory and strategy: Theory, application and managerial implications. *Strategic Management J.* **15** 167–178.

Lindholm, A. 1996. An economic system of technology-related acquisitions and spin-offs. Working paper no. 33. ESRC Centre for Business Research, University of Cambridge, Cambridge, UK.

Mason, C. 2007. Venture capital: A geographical perspective. In H. Landström (ed.), *Handbook of Research on Venture Capital*: 86-112. Cheltenham: Edward Elgar.

Maula, M., G. Murray. 2000. Corporate venture capital and the exercise of the options to acquire. *Proceedings of the R&D Management Conference*, Manchester, UK. 10-12 July.

Miles, M. P., J. G. Covin. 2002. Exploring the practice of corporate venturing: Some common forms and their organizational implications. *Entrepreneurship Theory & Practice*, **26**(3) 21-40.

Miles, M. B., A. M. Huberman. 1994. *Qualitative Data Analysis: An Expanded Sourcebook*. Sage, Thousand Oaks, CA.

Rasmusen, E. 1988. Entry for Buyout. *J. Indust. Econom.* **36**(3) 281–299.

Reinganum, J. F. 1983. Uncertain innovation and the persistence of monopoly. *Amer. Econom. Rev.* **73**(4) 741–748.

Scherer, F. M., D. Ross. 1990. *Industrial Market Structure and Economic Performance*, 3rd ed. Houghton Mifflin, Boston, MA.

Schumpeter, J. 1912. *The Theory of Economic Development*. Harvard University Press, Cambridge, MA.

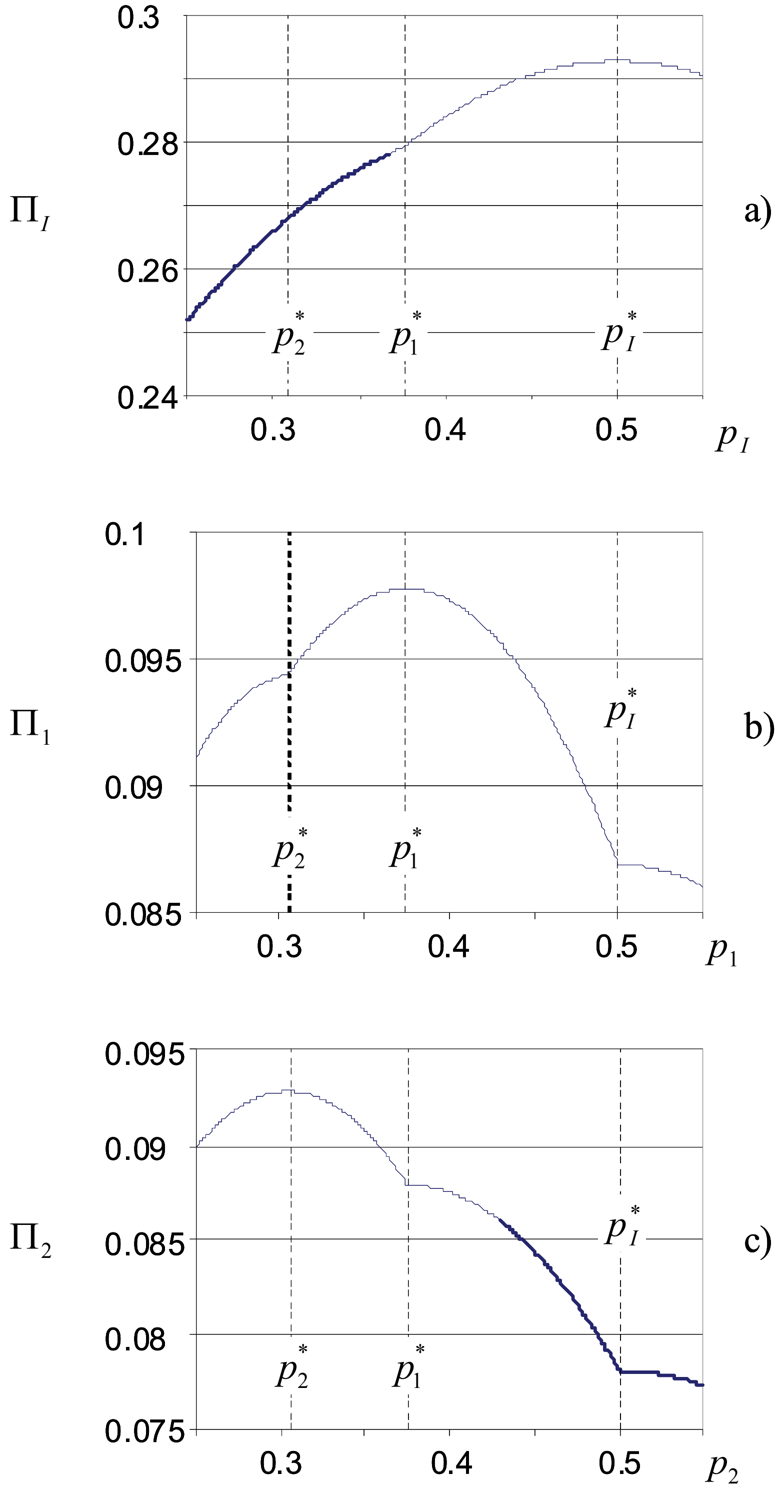
Solid State Technology. 2010. Gary Smith EDA market statistics 2010: Summary, accessed 3 January 2013 at http://www.electroiq.com/content/eiq/en/articles/sst/2010/07/gary-smith_eda_market.html.

Stinchcombe, A. L. 1965. Organizations and social structure. J. G. March, ed. *Handbook of Organizations*. Rand-McNally, Chicago, IL, 142-193.

Sykes, H. B., Z. Block. 1989. Corporate venturing obstacles—sources and solutions. *Journal of Business Venturing* **4** 159-167.

Figures

Figure 1 Firms' Payoffs when Deviating from Equilibrium, for *N*=2 and π(*p*) = 1 – *p*



Appendix

Proof of Lemma 2

Assume there was an equilibrium in which two or more firms picked the same success probability. Renumber firms, including I, such that $p_0 \geq \ldots > p_k = \ldots = p_{k+m} > \ldots \geq p_N$. We denote $p_k = \ldots = p_{k+m}$ by $\hat{p}$. At least one of firms k to $k + m$ is an entrant, and we order the firms such that firm k is an entrant. Using h_k defined in Definition 1, we can write firm k's profit function in case of a small deviation to larger or smaller values of p as follows (with $\varepsilon > 0$):

$$\Pi_k(\hat{p}+\varepsilon) = (\hat{p}+\varepsilon)\left(\prod_{i=k+m+1}^{N}(1-p_i)\right)(1-\hat{p})^m(\pi(\hat{p}+\varepsilon)-h_k),$$

$$\Pi_k(\hat{p}-\varepsilon) = (\hat{p}-\varepsilon)\left(\prod_{i=k+m+1}^{N}(1-p_i)\right)((1-\hat{p})^m(\pi(\hat{p}-\varepsilon)-h_k)+(1-(1-\hat{p})^m)\big(\pi(\hat{p}-\varepsilon) - \pi(\hat{p})\big).$$

Differentiating with respect to ε and calculating the limit of ε going to zero from above, we obtain:

$$\left.\frac{d\Pi_k(\hat{p}+\varepsilon)}{d\varepsilon}\right|_{\varepsilon \xrightarrow{+} 0} = \left(\prod_{i=k+m+1}^{N}(1-p_i)\right)(1-\hat{p})^m\left(\pi(\hat{p})+\hat{p}\pi'(\hat{p})-h_k\right)$$

$$\left.\frac{d\Pi_k(\hat{p}-\varepsilon)}{d\varepsilon}\right|_{\varepsilon \xrightarrow{+} 0} = -\left(\prod_{i=k+m+1}^{N}(1-p_i)\right)\left((1-\hat{p})^m\left(\pi(\hat{p})+\hat{p}\pi'(\hat{p})-h_k\right)+(1-(1-\hat{p})^m)\hat{p}\pi'(\hat{p})\right)$$

A necessary condition for the candidate equilibrium to exist is that both of the above terms are non-positive. However, if $\left.\frac{d\Pi_k(\hat{p}+\varepsilon)}{d\varepsilon}\right|_{\varepsilon \xrightarrow{+} 0} \leq 0$, this implies that $\left.\frac{d\Pi_k(\hat{p}-\varepsilon)}{d\varepsilon}\right|_{\varepsilon \xrightarrow{+} 0} > 0$, because $(1-(1-\hat{p})^m)\hat{p}\pi'(\hat{p}) < 0$. Hence, an equilibrium of the type specified in the proposition cannot exist.

Proof of Lemma 3

To start the induction argument, notice that $h_1 = \bar{p}_0\pi(\bar{p}_0) > h_0 = 0$, which implies that $\bar{p}_0 > \bar{p}_1$ due to concavity of $p\pi(p)$. Assume that $h_k > h_{k-1} > .. > h_0$ and that $\bar{p}_0 > \bar{p}_1 > \cdots > \bar{p}_k$. Now, using (9), one can derive that $h_{k+1} = h_k + \bar{p}_k(\pi(\bar{p}_k) - h_k)$. Since i) h_k is the expected value of the best project among projects 0, 1, …, k-1, ii) $\pi(p)$ is decreasing in p, and iii) $\bar{p}_j > \bar{p}_k$ for all $j < k$, it follows that $\pi(\bar{p}_k) > h_k$. Hence, $h_{k+1} > h_k$. This, in turn, implies that $\bar{p}_k > \bar{p}_{k+1}$, which proves part (i) of Lemma 3.

Consider an R&D portfolio consisting of i+1 projects where the projects have been renamed such that $p_0 \geq p_1 \geq \ldots \geq p_i$. The expected value of the best project is:

$$E[V_{max}] = \sum_{m=0}^{i} p_m \pi(p_m) \prod_{j=m+1}^{i} (1 - p_j).$$

Maximizing E[V_{max}] yields the first-order conditions (10), which proves part (ii) of the lemma.

Proof of Proposition 1

The proof proceeds as follows. First (a), starting from the assumption that $p_I > p_1 > ... > p_N$ in the sought-for equilibrium, we characterize the equilibrium candidate, show that it exists, and show that no player k has an incentive to deviate to some $p_k' \in [p_{k-1}^*, p_{k+1}^*]$. Having thus shown "local" stability of the equilibrium candidate, we then also show (b) that "non-local" deviations that change the order of p's (i.e., deviations from p_k to some $p_k' < p_{k+1}^*$ or $p_k' > p_{k-1}^*$) are not attractive.

Now, Π_I consists of three additive terms that capture the cases that (a) two or more entrants are successful (first terms), (b) exactly one entrant is successful (second term), and (c) no entrant is successful (third term):

$$\Pi_I = \sum_{j=2}^{N}\sum_{k=1}^{j-1} p_j p_k \pi(p_k) \prod_{\substack{m=k+1 \\ m\neq j}}^{N} (1-p_m) + p_I \pi(p_I) \sum_{j=1}^{N} p_j \prod_{\substack{m=1 \\ m\neq j}}^{N} (1-p_m) + p_I \pi(p_I) \prod_{j=1}^{N} (1-p_j)$$

Deriving the incumbent's first-order condition yields (10) with $k = 0$, and it follows that $p_I^* = \bar{p}_0 = \tilde{p}$. For entrant k, the expected profit can be written as follows:

$$\Pi_k = p_k \left(\prod_{j=k+1}^{N} (1 - p_j) \right) (\pi(p_k) - h_k),$$

where h_k is defined in Definition 1. Deriving entrant k's first-order condition yields (10) with $k > 0$, and it follows that $p_k^* = \bar{p}_k$. This proves that the success probability characterized in Proposition 1 constitute an equilibrium, except for showing that "non-local" deviations are not profitable.

Assume now that k deviates from p_k^* to some higher success probability p_k' such that $p_k' \in [p_m^*, p_{m-1}^*]$, where $m < k$. The optimal choice of p_k' within this interval is given by the first-order condition (10) which yields $\bar{p}_m$. We now show that a deviation to $p_k' = \bar{p}_m$ results in lower expected profit than $p_k^* = \bar{p}_k$. First, $p_k' = p_m^*$ cannot be (locally) optimal since, as we show in Lemma 2, there is always an incentive to deviate to slightly smaller or larger values of p when two players choose identical actions. Since the optimal choice of p_k' in $[p_m^*, p_{m-1}^*]$ is p_m^*, it is not profitable to choose a slightly larger value than p_m^*. Hence, as $\prod_I$ is continuous at $p_k' = p_m^*$, there exists some $p_k' \in [p_{m+1}^*, p_m^*)$ resulting in greater profit than $p_k' = p_m^*$. Applying this argument repeatedly finally shows that some p_k' in $[p_{k+1}^*, p_{k-1}^*)$ is more attractive than any p_k' > p_{k-1}^*. Hence, no profitable deviation exists for k to values of p_k' larger than p_{k-1}^*. A similar argument establishes that there is no profitable deviation to some $p_k' \in [p_{m+1}^*, p_m^*]$, where $m > k$. Finally, we need to show that for the incumbent also, a non-local deviation cannot be profitable. Assume that the incumbent deviates from p_0^* to some p_I' such that $p_I' \in [p_{m+1}^*, p_m^*]$, $0 < m$. To simplify expressions, denote by S the number of successful projects among entrants $m+1$ to N. Also, define $P(S)$ as the probability of exactly S successful projects among entrants $m+1$ to N and $E(\Pi_I|S)$ as the incumbent's profit conditional on S. Furthermore, we introduce $\hat{h}_{k+1} = \hat{h}_k + p_{k+1}^*\left(\pi(p_{k+1}^*) - \hat{h}_k\right)$ and $\hat{h}_0 = 0$ where $\hat{h}_k$ is the expected value of the best project among entrants $\{1, 2,...,k\}$. It follows from Lemma 3 that $h_k \geq \hat{h}_k$. Using the above notation, the incumbent's expected profit when deviating to p_I' can be written as:

$$\Pi_I = \sum_{j=2}^{N-m} P(S=j)E\left(\Pi_I|S=j\right) + \left(1 - \sum_{j=2}^{N-m} P(S=j)\right)\left(\pi(p_I')p_I' + (1-p_I')\left(P(S=1)\hat{h}_m + P(S=0)\sum_{j=1}^{m} p_j \hat{h}_{j-1} \prod_{k=j+1}^{m}(1-p_k)\right)\right).$$

The first term in $\prod_I$ is the incumbent's expected profit when more than two projects of higher value than $\pi(p_I')$ succeed. The second term is the expected profit in the complementary case where the incumbent either obtains the profit equal to the value of its own project, if successful, or the value of the second-best project among entrants 1 to m. Maximizing the incumbent's expected profit with respect to p_I' yields:

$$\pi(p_I') + p_I'\pi'(p_I') - P(S=1)\hat{h}_m - P(S=0)\sum_{j=1}^{m} p_j \hat{h}_{j-1} \prod_{k=j+1}^{m}(1-p_k).$$

Since $p_I' \leq p_m^*$, it follows from concavity of $p\pi(p)$ that $\pi(p_I') + p_I\pi'(p_I') \geq h_m$, and we have:

$$\pi(p_I') + p_I\pi'(p_I') - P(S=1)\hat{h}_m - P(S=0)\sum_{j=1}^{m} p_j \hat{h}_{j-1} \prod_{k=j+1}^{m}(1-p_k) \geq$$

$$h_m - P(S=1)\hat{h}_m - P(S=0)\sum_{j=1}^{m} p_j \hat{h}_{j-1} \prod_{k=j+1}^{m}(1-p_k) =$$

$$P(S=1)(h_m - \hat{h}_m) + P(S=0)\sum_{j=1}^{m} p_j (h_m - \hat{h}_{j-1}) \prod_{k=j+1}^{m}(1-p_k) + \left(1 - P(S=1) - P(S=0)\sum_{j=1}^{m} p_j \prod_{k=j+1}^{m}(1-p_k)\right)h_m > 0,$$

where the last inequality follows from $h_m > \hat{h}_m$, $h_m > h_{j-1} > \hat{h}_{j-1}$ for j-1 < m, and

$\sum_{j=1}^{m} p_j \prod_{k=j+1}^{m}(1-p_k) \equiv 1-\prod_{k=1}^{m}(1-p_k) < 1$. Therefore, the optimal deviation for $p_I' \in [p_{m+1}^*, p_m^*]$ is $p_I' = p_m^*$. A similar argument shows that the optimal deviation for $p_I' \in [p_m^*, p_{m-1}^*]$ is $p_I' = p_{m-1}^*$. Hence, as $\prod_I$ is continuous at $p_k' = p_m^*$, $p_I' = p_{m-1}^*$ results in greater profit for the incumbent than $p_I' = p_m^*$. Applying this argument repeatedly shows the incumbent has no incentive to deviate to some $p_I' \leq p_I^*$. Hence, $p_I^* = \bar{p}_0$ and $p_i^* = \bar{p}_i$ for $i = 1,\ldots,N$ constitute an equilibrium. Finally, a social planner maximizes the expected highest value of the projects, E[V_{max}]. Then, it follows from Lemma 3 that the equilibrium R&D choices are welfare maximizing, which proves part (i) of the Proposition.

In order to prove part (ii), we proceed in three steps. First, it follows from Lemma 3 that p_{k-1}^* maximizes h_k given the choices of the other firms. Hence, h_k decreases when entrant (k-1)'s success probability is continuously decreased from p_{k-1}^* to p_k^*. This, in turn, implies that the decrease in p_{k-1} increases the expected profit of entrant k. Finally, as $\Pi_k = \Pi_{k-1}$ for $p_{k-1} = p_k^*$, $\Pi_k^* < \Pi_{k-1}^*$ in equilibrium in which $p_{k-1} = p_{k-1}^*$. It only remains to also show that $\Pi_I^* > \Pi_1^*$. To see this, note that $\Pi_I^* \geq \widetilde{p}\pi(\widetilde{p})$, since this is the value that the incumbent can secure without any acquisition, and since it will only acquire an entrant if doing so increases its profit. Hence, $\Pi_1^* < p_1^*\pi(p_1^*) < \widetilde{p}\pi(\widetilde{p}) \leq \Pi_I^*$, which completes the proof.

Proof of Proposition 2

Consider the candidate equilibrium with $p_1 > p_2 > \ldots > p_N > p_I$. Define A as the expected value of the highest realized value among the entrants $1, \ldots, N-1$, and B as the expected value of the second-highest realized value among all entrants. It follows from these definitions that $A > B$. We can now write the expected payoffs of the incumbent and of entrants 1 and N as follows:

$$\Pi_1 = p_1\pi(p_1)(1-p_I)\prod_{k=2}^{N}(1-p_k)$$
$$\Pi_N = p_N(1-p_I)(\pi(p_N)-A)$$
$$\Pi_I = p_I\pi(p_I)+(1-p_I)B$$

The resulting first-order conditions are:

$$\pi(p_1)+p_1\pi'(p_1) = 0$$
$$\pi(p_N)+p_N\pi'(p_N) = A$$
$$\pi(p_I)+p_I\pi'(p_I) = B$$

Since $p\pi(p)$ is concave and increasing in p for $p < \widetilde{p}$, the first-order conditions are fulfilled for $\tilde{p} = p_1 > p_I > p_N$. Hence, there cannot exist an equilibrium in which $p_1 > p_2 > \ldots > p_N > p_I$.

Proof of Proposition 3

(i) Analytically solving the system of first-order conditions for the candidate equilibrium with $p_1 > p_I > p_2$ yields the unique solution of $p_1 = 0.5$, $p_I \approx 0.461$, and $p_2 \approx 0.308$. This, however, turns out not to be an equilibrium. For example, deviating from 0.5 to 0.4 increases firm 1's expected payoff from approximately 0.0931 to approximately 0.0972. Thus, there exists no equilibrium with $p_1 > p_I > p_2$. Together with Proposition 2 and Proposition 3 this proves that the only equilibrium is given by $p_I = 0.5$, $p_1 = 0.375$, and $p_2 \approx 0.305$.

(ii) Solving the system of first-order conditions for the candidate equilibrium with $p_1 > p_I > p_2 > p_3$ yields the unique solution of $p_1 = 0.5$, $p_I \approx 0.445$, $p_2 \approx 0.307$, and $p_3 \approx 0.260$. However, deviating from 0.5 to 0.4 increases firm 1's payoff from approximately 0.0712 to approximately 0.0724. Note that, due to the need to calculate roots of higher-order polynomials, the equilibrium had to be calculated numerically. Regarding the second part of the statement, starting with the assumption that $p_1 > p_2 > p_I > p_3$ and (numerically) solving the system of first-order conditions leads to a unique solution that, however, does not fulfill the above sequence of inequalities: $p_1 = 0.5$, $p_2 \approx 0.375$, $p_I \approx 0.414$, and $p_3 \approx 0.264$. That is, there is no equilibrium in which $p_1 > p_2 > p_I > p_3$. Together with Proposition 1 and Proposition 2 this proves that the only equilibrium is given by $p_I = 0.5$, $p_1 = 0.375$, $p_2 \approx 0.305$, and $p_3 \approx 0.274$.

Proof of Proposition 4

Suppose that at least one of the entrants is successful such that the incumbent has an interest in making an acquisition. If the incumbent makes the offer, it acquires the entrant with the most valuable technology at an acquisition price of zero. Instead, if the entrants make the offers, the equilibrium outcome at the acquisition stage is as described in Lemma 1. Consider an equilibrium where $p_2^* \leq p_1^* \leq p_I^*$. Then, the profit function of the incumbent can be written as:

$$\Pi_I(p_I) = \begin{cases} bE[V_{max}] + (1-b)\big(p_2^* p_1^* \pi(p_1^*) + (1 - p_2^* p_1^*) p_I \pi(p_I)\big) & if \quad p_2^* \leq p_1^* \leq p_I \\ bE[V_{max}] + (1-b)\big(p_I \pi(p_I) + (1 - p_I) p_2^* p_1^* \pi(p_1^*)\big) & if \quad p_2^* \leq p_I < p_1^* \\ bE[V_{max}] + (1-b)\big(p_I \pi(p_I) + (1 - p_I) p_2^* p_1^* \pi(p_1^*)\big) & if \quad p_I < p_2^* \leq p_1^* \end{cases}$$

where $E[V_{max}] = p_k \pi(p_k) + (1 - p_k) p_j \pi(p_j) + (1 - p_k)(1 - p_j) p_i \pi(p_i)$ for $p_i \geq p_j \geq p_k$ is the expected value of the best technology. The profit functions of the entrants are given by the profit function in equation (4) multiplied by *(1 - b)*. If the incumbent chooses $p_I^* = \bar{p}_0$, it follows immediately from the proof of Proposition 1 that the entrants choose $p_1^* = \bar{p}_1$ and $p_2^* = \bar{p}_2$ in equilibrium.

For $p_2^* \leq p_1^* \leq p_I$, the first-order condition of the incumbent is given by:

$$\frac{\partial \Pi_I(p_I)}{\partial p_I} = 0 \Leftrightarrow \pi(p_I) + p_I \pi'(p_I) = 0,$$

which implies that $p_I^* = \bar{p}_0$ is a local maximum. Consider a deviation to some $p_I' \in [p_2^*, p_1^*]$. Then, the first-order condition is given by:

$$\pi(p_I{}') + p_I{}'\pi'(p_I{}') - \frac{b(1-p_2^*) + p_2^*(1-b)}{1-p_2^*b} p_1^*\pi(p_1^*) = 0$$

Notice that (a) $\frac{b(1-p_2^*)+p_2^*(1-b)}{1-p_2^*b} < 1$, and (b) $p_1^*\pi(p_1^*) < p_I^*\pi(p_I^*)$ as $p_I^* = \tilde{p}$. Hence, the incumbent's first-order condition is satisfied for some $p_I > p_1^*$, which implies that $\Pi_I(p_I)$ is increasing in p_I for $p_2^* \leq p_I < p_1^*$. Finally, since $\Pi_I(p_I)$ is continuous at $p_I = p_1^*$, it follows that $p_I = p_1^* = \bar{p}_0$ yields higher profit for the incumbent than any $p_2^* \leq p_I < p_1^*$. A similar argument establishes that that there does not exist a profitable deviation to some $p_I < p_2^*$. This proves the existence of the candidate equilibrium.

Proof of Proposition 5

Consider a game with two incumbents and one entrant. Denote the incumbents by 1 and 2 and the entrant by *E*.

Lemma A.1. *Suppose that there are two incumbents and one entrant and that the realized value of incumbent j's project is greater than or equal to the realized value of incumbent i's project, $\pi_j > \pi_i$. If the realized value of the entrant's project, π_E, is greater than π_j, then incumbent j acquires the entrant at a price of $\pi_E - \pi_j$. Otherwise, no acquisition takes place.*

Proof. Follow standard Bertrand competition logic.

We are now ready to prove Proposition 5. Consider first a candidate equilibrium where $p_E^* \leq p_2^* \leq p_1^*$. Using Lemma A.1, the profit functions can be written as:

$$\Pi_E(p_E) = \begin{cases} p_E\big(\pi(p_E) - p_2^*\pi(p_2^*) - (1-p_2^*)p_1^*\pi(p_1^*)\big) & if \quad p_E \leq p_2^* \leq p_1^* \\ (1-p_2^*)p_E\big(\pi(p_E) - p_1^*\pi(p_1^*)\big) & if \quad p_2^* < p_E \leq p_1^* \\ (1-p_1^*)(1-p_2^*)p_E\pi(p_E) & if \quad p_2^* \leq p_1^* < p_E \end{cases}$$

$$\Pi_1(p_1) = \begin{cases} (1-p_2^*)p_1\pi(p_1) & if \quad p_E^* \leq p_2^* \leq p_1 \\ p_1\big(\pi(p_1) - p_2^*\pi(p_2^*)\big) & if \quad p_E^* \leq p_1 < p_2^* \\ p_1\big(\pi(p_1) - p_2^*\pi(p_2^*)\big) & if \quad p_1 < p_s^* \leq p_E^* \end{cases}$$

$$\Pi_2(p_2) = \begin{cases} (p_2\big(\pi(p_2) - p_1^*\pi(p_1^*)\big) & if \quad p_E^* \leq p_2 \leq p_1^* \\ (1-p_1^*)p_2\pi(p_2) & if \quad p_E^* \leq p_1^* < p_2 \\ p_2\big(\pi(p_2) - p_1^*\pi(p_1^*)\big) & if \quad p_2 < p_E^* \leq p_1^* \end{cases}$$

Using Definition 1, the first-order conditions can for $p_E \leq p_2 \leq p_1$ be written as:

$$\frac{\partial\Pi_1(p_1)}{\partial p_1} = 0 \Leftrightarrow \pi(p_1) + p_1\pi'(p_1) = h_0 \Leftrightarrow p_1^* = \bar{p}_{0,}$$

$$\frac{\partial \Pi_2(p_2)}{\partial p_2} = 0 \Leftrightarrow \pi(p_2) + p_2\pi'(p_2) = h_1 \Leftrightarrow p_2^* = \bar{p}_1,$$

$$\frac{\partial \Pi_E(p_E)}{\partial p_E} = 0 \Leftrightarrow \pi(p_E) + p_E\pi'(p_E) = h_2 \Leftrightarrow p_E^* = \bar{p}_2.$$

Following the arguments in the proof of Proposition 1, the success probabilities constitute an equilibrium only if the firms do not have an incentive to make a non-local deviation (i.e., a deviation that changes the relative ranking of the firms' success probabilities). Consider first deviations by *E*. Suppose that the entrant chooses some $p_2^* < p_E \leq p_1^*$. Then, the first-order condition is given by

$$\pi(p_E) + p_E\pi'(p_E) = p_1^*\pi(p_1^*).$$

The first-order condition is satisfied for $p_2^* = p_E$, which implies that $\Pi_E(p_E)$ is decreasing in p_E for $p_2^* < p_E \leq p_1^*$. Since $\Pi_E(p_E)$ is continuous at $p_2^* = p_E$, it follows that $p_E = p_E^* = \bar{p}_2$ yields higher profit than any $p_2^* < p_E \leq p_1^*$. A similar argument establishes that there does not exist a profitable deviation to some $p_2^* \leq p_1^* < p_E$.

We consider only non-local deviations by incumbent *1* but it can be shown in a similar manner that there does not exist a profitable deviation for incumbent *2*. Suppose that *1* chooses some $p_E^* \leq p_1 < p_2^*$. Then, the first-order condition characterizing the optimal success probability is given by:

$$\pi(p_1) + p_1\pi'(p_1) = p_2^*\pi(p_2^*).$$

It follows from Lemma 3 part (ii) that $p_2^*\pi(p_2^*) < p_1^*\pi(p_1^*) = \tilde{p}\pi(\tilde{p})$. Hence, the first-order condition holds for some $p_2^* < p_1$. Therefore, $\Pi_1(p_1)$ is increasing in p_1 in the interval considered. Since $\Pi_1(p_1)$ is continuous at $p_2^* = p_1$, it follows that $p_1 = p_1^* = \bar{p}_0$ yields higher profit than any $p_E^* \leq p_1 < p_2^*$. Finally, it can be shown in a similar manner that there does not exist a profitable deviation to some $p_1 < p_E^* \leq p_2^*$. This proves existence of the equilibrium.

In order to show that this is the unique equilibrium in pure strategies, consider first a candidate equilibrium in which $p_2^* < p_E^* \leq p_1^*$. Then, using Lemma A.1, the profit functions are given by:

$$\Pi_E(p_E) = (1 - p_2^*)p_E\big(\pi(p_E) - p_1^*\pi(p_1^*)\big)$$

$$\Pi_1(p_1) = (1 - p_2^*)p_1\pi(p_1)$$

$$\Pi_2(p_2) = p_2\big(\pi(p_2) - p_1^*\pi(p_1^*)\big)$$

Maximizing profit show that the incumbents choose $p_1^* = \bar{p}_0$ and $p_2^* = \bar{p}_1$. The entrant chooses also $p_E^* = \bar{p}_1$ in the candidate equilibrium. However, it follows from the first part of the proof that this cannot constitute an equilibrium, because there then would exist a profitable deviation for the entrant to $p_E^* = \bar{p}_2$. A similar argument establishes that there cannot exist an equilibrium in pure strategies in which $p_2^* \leq p_1^* < p_E^*$.

Proof of Proposition 7

We make some assumptions to ensure that investment increases expected R&D performance and that the first-order conditions characterize an equilibrium:

Assumption 1.A. *$p(\phi_i)$ $\pi(\phi_i)$ - $c(\phi_i)$ is concave and takes on a global maximum for some $\phi_i = \tilde{\phi}$.*

Assumption 2.A. *$p'(\phi_i) \geq 0$ and $\pi'(\phi_i) \geq 0$ with at least one strict inequality.*

Assumption 3.A. *$0 \leq p(\phi_i) < 1$ for all $\phi_i \leq \tilde{\phi}$ and $p'(\phi_i)$ is concave in ϕ_i.*

Assumption 4.A. *$c(0) = c'(0) = 0$ and $c(\phi_i)$ is sufficiently convex to ensure that the second-order conditions associated to the firms' maximization problems are satisfied.*

Consider the candidate equilibrium in which $\phi_I^* \geq \phi_2^* \geq \phi_1^*$. Then, the expected profits of the firms can be written as:

$$\Pi_I(\phi_I, \phi_1^*, \phi_2^*) = p(\phi_I)\pi(\phi_I) + (1 - p(\phi_I))p(\phi_1^*)p(\phi_2^*)\pi(\phi_1^*) - c(\phi_I),$$
$$\Pi_2(\phi_I^*, \phi_1^*, \phi_2) = (1 - p(\phi_I^*))p(\phi_2)(\pi(\phi_2) - p(\phi_1^*)\pi(\phi_1^*)) - c(\phi_2),$$
$$\Pi_1(\phi_I^*, \phi_1, \phi_2^*) = p(\phi_1)(1 - p(\phi_I^*))(1 - p(\phi_2^*))\pi(\phi_1) - c(\phi_1).$$

The corresponding first-order conditions are:

$$\frac{\partial \Pi_I}{\partial \phi_I} = 0 : p'(\phi_I^*)\pi(\phi_I^*) + p(\phi_I^*)\pi'(\phi_I^*) - c'(\phi_I^*) = \underbrace{p'(\phi_I^*)p(\phi_1^*)p(\phi_2^*)\pi(\phi_1^*)}_{A1},$$

$$\frac{\partial \Pi_2}{\partial \phi_2} = 0 : p'(\phi_2^*)\pi(\phi_2^*) + p(\phi_2^*)\pi'(\phi_2^*) - c'(\phi_2^*) = \underbrace{p(\phi_I^*)(p'(\phi_2^*)\pi(\phi_2^*) + p(\phi_2^*)\pi'(\phi_2^*))}_{B1} + \underbrace{p'(\phi_2^*)(1 - p(\phi_I^*))p(\phi_1^*)\pi(\phi_1^*)}_{B2},$$

$$\frac{\partial \Pi_1}{\partial \phi_1} = 0 : p'(\phi_1^*)\pi(\phi_1^*) + p(\phi_1^*)\pi'(\phi_1^*) - c'(\phi_1^*) =$$
$$\underbrace{p(\phi_I^*)(p'(\phi_1^*)\pi(\phi_1^*) + p(\phi_1^*)\pi'(\phi_1^*))}_{C1} + \underbrace{p'(\phi_1^*)(1 - p(\phi_I^*))p(\phi_2^*)\pi(\phi_1^*)}_{C2} + \underbrace{p(\phi_1^*)(1 - p(\phi_I^*))p(\phi_2^*)\pi'(\phi_1^*)}_{C3}.$$

Under the assumptions A.1.-A.4 and under the assumption that $\phi_I^* > \phi_2^* > \phi_1^*$, the right hand side of the first-order condition associated with the incumbent's problem is less than the right hand side of the first-order condition associated with entrant 2's problem, because *B1 > A1* and *B2 > 0*. This, in turn, is less than the right hand side of the first-order condition associated with entrant 1's problem, because *C1 > B1*, *C2 > B2*, and *C3 > 0*. Hence, as the left hand sides are decreasing in the R&D intensity, the first-order conditions are consistent with an equilibrium in which $\phi_I^* > \phi_2^* > \phi_1^*$.

Finally, we need to show that there does not exist a profitable, non-local deviation for any of the firms. If the incumbent deviates to some $\phi_2^* > \phi_I' \geq \phi_1^*$, the profit function remains the same as the one derived above. Hence, as ϕ_I^* is optimal, there exists no profitable deviation to some $\phi_2^* > \phi_I' \geq \phi_1^*$.

Consider instead a deviation to some $\phi_I^* > \phi_I'$. Then, the profit function of the incumbent becomes:

$$\Pi_I(\phi_I^{'},\phi_1^{*},\phi_2^{*}) = p(\phi_1^{*})p(\phi_2^{*})\pi(\phi_1^{*}) + (1 - p(\phi_1^{*})p(\phi_2^{*}))p(\phi_I^{'})\pi(\phi_I^{'}) - c(\phi_I^{'}).$$

The corresponding first-order condition is:

$$p'(\phi_I^{'})\pi(\phi_I^{'}) + p(\phi_I^{'})\pi'(\phi_I^{'}) - c'(\phi_I^{'}) = \underbrace{p(\phi_1^{*})p(\phi_2^{*})(p'(\phi_I^{'})\pi(\phi_I^{'}) + p(\phi_I^{'})\pi'(\phi_I^{'}))}_{D1}.$$

Compare this first-order condition to the one associated with entrant 1. Since $p(\phi_1^{*})p(\phi_2^{*}) < p(\phi_I^{*})$, it follows that *D1 < C1* for $\phi_1 = \phi_I^{'}$. Furthermore, as *C2 > 0* and *C3 > 0*, we conclude that $\Pi_I(\phi_I^{'},\phi_1^{*},\phi_2^{*})$ is increasing in $\phi_I^{'}$ for all $\phi_1^{*} > \phi_I^{'}$. Furthermore, as the incumbent's profit function is continuous at $\phi_1^{*} = \phi_I$, it follows from the analysis that $\Pi_I(\phi_I^{'},\phi_1^{*},\phi_2^{*})$ has a global maximum at $\phi_I^{*} = \phi_I^{'}$. This proves that there exists no profitable deviation for the incumbent, and it can be shown in a similar manner that the entrants also do not have an incentive to deviate in equilibrium.

In order to show that this is the unique equilibrium in pure strategies, consider an equilibrium in which $\phi_2^* > \phi_I^* > \phi_1^*$. The profit functions of I and 2 are then:

$$\Pi_I(\phi_I,\phi_1,\phi_2) = \rho(\phi_I)\pi(\phi_I) + (1 - \rho(\phi_I))\rho(\phi_1)\rho(\phi_2)\pi(\phi_1) - c(\phi_I),$$
$$\Pi_2(\phi_I,\phi_1,\phi_2) = \rho(\phi_2)(\pi(\phi_2) - \rho(\phi_I)\pi(\phi_I) - (1 - \rho(\phi_I))\rho(\phi_1)\pi(\phi_1)) - c(\phi_2).$$

The corresponding first-order conditions are:

$$\rho'(\phi_I)\pi(\phi_I) + \rho(\phi_I)\pi'(\phi_I) - c'(\phi_I) = \rho'(\phi_I)\rho(\phi_1)\rho(\phi_2)\pi(\phi_1),$$
$$\rho'(\phi_2)\pi(\phi_2) + \rho(\phi_2)\pi'(\phi_2) - c'(\phi_2) = \rho'(\phi_2)\rho(\phi_I)\pi(\phi_I) + \rho'(\phi_2)(1 - \rho(\phi_I))\rho(\phi_1)\pi(\phi_1).$$

The right hand side of the first-order condition associated with the entrant 2's problem is greater than the right side of the first-order condition associated with incumbent's problem for any $\phi_2 = \phi_I$. As the left hand side is decreasing in the R&D intensity of the firm considered, the two first-order conditions hold simultaneous for some $\phi_2 < \phi_I$, which contradicts the initial assumption of $\phi_2^* > \phi_I^* \geq \phi_I^*$. It can be shown in a similar manner that there does not exist an equilibrium in which $\phi_2^* \geq \phi_I > \phi_I^*$.