And the Winner is – Acquired.

Entrepreneurship as a Contest Yielding Radical Innovations

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Abstract

New entrants to a market tend to be superior to incumbents in originating radical innovations. We provide a new explanation for this phenomenon, based on markets for technology. It applies in industries where successful entrepreneurial firms, or their technologies, are acquired by incumbents that then commercialize the innovation. To this end 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 accompanies 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 performs the least radical project. Entrants pick pairwise different projects; the bigger the number of entrants, the more radical the most radical project. Generally, entrants tend to choose more radical R&D approaches and generate the highest value innovation in case of success. We illustrate our theoretical findings by a qualitative empirical study of the Electronic Design Automation industry, and derive implications for research and management.

Keywords: radical innovation; entrant; incumbent; acquisition; markets for technology; game theory

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1. Introduction

What is the division of labor in the production of innovations among large established firms and small entrepreneurial ventures? This fundamental question has attracted the interest of scholars and policy makers alike, and has spawned a broad literature going back to Schumpeter (1912) and as far as Say (1827). While the evidence is somewhat mixed, the overall picture is that incumbent firms develop most of the incremental innovations but that entrants play an important role in the creation of breakthroughs (e.g., Scherer and Ross, 1990; van Praag and Versloot, 2007). Baumol (2010, p. 25) explains this as the result of a process where "[T]he giant companies may account for the major share of the economy's R&D financing, but these better established firms tend to minimize risk by specializing in incrementally improving the most promising of the radical innovations they purchase, license or adapt from the smaller firms that created them."

Early theoretical studies point out that incumbents have weaker incentives than start-ups to invest in R&D in situations where they would replace their own products (Arrow, 1962) but that they have stronger incentives to invest if their market power is threatened by entry (Gilbert and Newbury, 1982; Reinganum, 1983). However, there is an important distinction with respect to how the innovations of start-ups are commercialized. The abovementioned models assume that start-ups enter the product market and compete with incumbents. Yet, as Baumol (2010) points out, a cooperative agreement between an entrant and an incumbent regarding commercialization, in general should be superior both because of increased market power and because entrants typically lack the broad resource bases of incumbents. Reflecting this point, some more recent theoretical studies allow for a successful entrant to be acquired by (or to license its invention to) an incumbent (Gans and Stern, 2000; Kleer and Wagner, 2013).

Our paper contributes to this stream of literature. However, our approach differs in two respects from earlier work. First, we note that in many industries the number of start-ups seeking to be acquired is, for each technological innovation, higher than the number of start-ups that eventually succeed. In such a market, start-ups compete to be acquired. Second, with the notable exception of Färnstrand Damsgaard et al. (2009), the previous studies choose innovation effort—i.e., budget spent—as the players' choice variable. However, selecting an R&D project is often a question of which path to follow rather than how much to invest. As an illustration, consider Vertex Pharmaceuticals (Pisano et al., 2006). With a given R&D budget, the biotech firm had to pick two from four promising drug candidates, each characterized by its own success probability, and value in case of success. In addition, the typically limited financial resources of entrants make it unlikely that they could achieve more radical innovations by outspending incumbents. Furthermore, in many industries—among them software and biotechnology—capital requirements in the early phases of R&D projects are modest, and so budget spent is not the most relevant lever for innovation radicalness. It is thus a plausible assumption that entrants distinguish themselves from incumbents by choosing more "radical" R&D approaches with lower success probability and concomitant higher value in case of success.

In our model, we consider an industry consisting of one incumbent and N entrants. The firms conduct R&D with the aim of developing an innovation at a fixed cost normalized to zero. Only the incumbent can commercialize an innovation, so the entrants' goal is to be acquired. The firms' choice variable is the success probability of their R&D projects, with projects with lower success probability having a higher value in case of success. All firms have access to the same R&D possibilities, described by a function linking the project's value in case of success to its 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, successful entrants compete to be acquired by the incumbent.

The main 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 with 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 are robust to changes in the timing of the 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. The economic intuition behind this result is related to the value of having the second best technology. The incumbent benefits from its technology both when it is best (and it is used to produce) and when it is second best (and it is used to reduce the price paid for the best technology). Therefore, the incumbent has an incentive to pursue a more incremental technology with a higher success probability than an entrant who only benefits from its technology when it is the best one and is acquired.

We illustrate this, using a qualitative empirical study of the electronic design automation (EDA) industry to support our analysis. This industry, which develops 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 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. Also in other industries we observe acquisitions that are consistent with the predictions of our model. The business press reports that biotech firm Gilead acquired Pharmasset since the latter had a better therapeutic concept against Hepatitis C virus (Bloomberg, 2011), and that Bristol-Meyers Squibb acquired Inhibitex in the same market in order to improve its own offering (Wall Street Journal, 2012). We will discuss the applicability of our results to other industry in more detail in the concluding section.

Our results that entrants originate more radical innovations seem in line with the literature. Yet, they are based on a fundamentally different mechanism than the findings in earlier studies: essentially, on the existence of a market for technology (e.g. Arora et al., 2001; Arora and Gambardella, 1994; Gans and Stern, 2003; Lamoreaux and Sokoloff, 1999) between entrants and incumbents. 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 or investment), and (b) entrants, if successful, need to be acquired in order to commercialize their innovations. The incumbent neither cannibalizes its own product when innovating nor does it protect an existing market. 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 technologies or entire firms are traded in this market—plays an important role in explaining the 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, 4 and 5 we introduce and analyze the model, and perform robustness checks and extensions. Section 6 provides a qualitative empirical study of the EDA industry to illustrate our analysis. In Section 7 we summarize and discuss our findings and conclude the paper.

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 (Hall, 1990; Lerner and Merges, 1998; Bloningen and Taylor, 2000; Lehto and Lehtoranta, 2006; Grimpe and Hussinger, 2008 and 2009).[1] In line with our analysis, Granstrand and Sjölander (1990) show that start-up innovations are more radical than those 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 gains from trade of technology, and well-established intellectual property rights and

[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.

involvement of professional intermediaries are found to increase the likelihood that these gains are realized by entrant and 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 modeled in detail the negotiations between an incumbent and an entrant over an innovation and showed how the acquisition price depends crucially on the strength of intellectual property protection and on the possibility of the entrant to enter the product market. This, in turn, determines the two firms' payoffs from and incentives to conduct R&D. Kleer and Wagner (2013) model competition between small and large firms for an exclusive patent, assuming R&D efficiency advantages for small firms and exploitation advantages for large firms. Among other things they derive, and confirm empirically, that acquisitions increase overall innovation output. Also Phillips and Zhdanov (2013) assume differences between small and large firms with respect to their costs of production and of R&D. Firms have the binary choice to conduct R&D or not. The authors find that both small and large firms attempt to innovate when acquisition is possible; however, with increasing size firms may find it preferable to buy successful small innovators. Compared to these studies, 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, and where competition between entrants affects their choices of strategy.

Our paper is related also 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 the 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]. The random variables describing success or failure of the N+1 firms are independently distributed. 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. Given that any firm for a given p will prefer the project with the highest value in case of success, the function $\pi(.)$ can be interpreted as describing the set of undominated projects. At this technological frontier, lower success probability implies higher rewards in case of success. 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

[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).

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 $\tilde{p} = 0.5$. 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.

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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 projects. 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 bargaining power is less critical in our framework (as we show formally in Section 5.2) since we do not study entrants' nor incumbent's R&D investments (as, e.g., Gans and Stern 2000)—which obviously are strongly affected by the surplus sharing rule—but rather their choice of success probabilities.

4. Solving the Model

In this subsection, we prove the existence of an equilibrium in which the incumbent picks the least radical project, and show that this equilibrium is welfare optimal; and prove the 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 initially examining the acquisition stage. Then, we turn to the R&D choices of the firms. We first look at a 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 a maximum of one entrant since it can use the technology of only 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:

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

If the realized values of the entrants' technologies are higher than the realized value of the incumbent's technology (situations represented by summands containing the factor $p_2 p_1$ in the above equations), the entrants are competing to be acquired. Then, the incumbent acquires the entrant with the most valuable technology (entrant 2, since we assume $p_2 \leq p_1$) at a price that secures the incumbent a profit equal to the value of the other entrant's technology (i.e, $\pi(p_1)$). 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 a 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 | *i*'s technology is best], (2)

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

The profit function of entrant *i* (shown for *i* = 1) requires distinguishing six cases depending on the relative sizes of p_1, p_2, and p_I:

$$\Pi_1(p_1) = \begin{cases} p_1(1-p_2)(1-p_I)\pi(p_1) + p_1 p_2\big(\pi(p_1) - \pi(p_2)\big) + p_1(1-p_2)p_I\big(\pi(p_1) - \pi(p_I)\big) & : p_1 \leq p_2 \leq p_I \\ p_1(1-p_I)(1-p_2)\pi(p_1) + p_1 p_I\big(\pi(p_1) - \pi(p_I)\big) + p_1(1-p_I)p_2\big(\pi(p_1) - \pi(p_2)\big) & : p_1 \leq p_I < p_2 \\ (1-p_2)p_1(1-p_I)\pi(p_1) + (1-p_2)p_1 p_I\big(\pi(p_1) - \pi(p_I)\big) & : p_2 < p_1 \leq p_I \\ (1-p_2)(1-p_I)p_1\pi(p_1) & : p_2 \leq p_I < p_1 \\ (1-p_I)p_1(1-p_2)\pi(p_1) + (1-p_I)p_1 p_2\big(\pi(p_1) - \pi(p_2)\big) & : p_I < p_1 \leq p_2 \\ (1-p_2)(1-p_I)p_1\pi(p_1) & : p_I < p_2 < p_1 \end{cases}$$

(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 yields the first-order conditions (FOCs) characterizing the equilibrium:

$$\frac{\partial \Pi_I(p_I)}{\partial p_I} = [p_2(1-p_1) + (1-p_2)p_1 + (1-p_2)(1-p_1)] \cdot [\pi(p_I) + p_I\pi'(p_I)] \Rightarrow \text{FOC:} \;\; \pi(p_I^*) = -p_I^*\pi'(p_I^*) \quad (5)$$

$$\frac{\partial \Pi_1(p_1)}{\partial p_1} = [(1-p_2)(1-p_I) + (1-p_2)p_I] \cdot [\pi(p_1) + p_1\pi'(p_1)] - (1-p_2)p_I\pi(p_I)$$

$$\Rightarrow \;\text{FOC:} \;\; \pi(p_1^*) - p_I^*\pi(p_I^*) = -p_1^*\pi'(p_1^*) \qquad (6)$$

$$\frac{\partial \Pi_2(p_2)}{\partial p_2} = [(1-p_1)(1-p_I) + p_1 + (1-p_1)p_I] \cdot [\pi(p_2) + p_2\pi'(p_2)] - p_1\pi(p_1) - (1-p_1)p_I\pi(p_I)$$

$$\Rightarrow \;\text{FOC:} \;\; \pi(p_2^*) - \left(p_1^*\pi(p_1^*) + (1-p_1^*)p_I^*\pi(p_I^*)\right) = -p_2^*\pi'(p_2^*) \;(7)$$

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] Comparing the LHS of equations (6) and (7) to that of (5) shows the additional terms that reflect how the existence of a second successful technology weakens the respective entrant's bargaining position and pushes it to pursue riskier projects.

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

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[4] The first-order condition for entrant 1, Equation (6), has a parallel with the models by Färnstrand Damsgaard 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.

equilibrium success probability given the R&D choices of the other firms. Note that our assumptions do not force the firms to pick differing R&D projects. Rather, this asymmetry arises endogenously.

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]

--- *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 in the literature. Note, however, that it is not based on the cannibalization effect since the incumbent is not present initially in the market segment considered. Instead, it derives from the fact that the incumbent but not the entrants, is

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 of 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.

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 because 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 because they can 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. A crucial assumption for this result is that there can be competition in the market for acquisitions, a point we will elaborate upon in Section 5.1.

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 does differentiation in the product space; 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 (subject to the condition $p_2 \leq p_1 \leq p_I$):

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

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 is twofold. First, it is optimal from a welfare point of view to have a firm choosing $\tilde{p}$. This firm picks the technology with the highest expected value, providing a fall-back option 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 5.4.

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 here is 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.*

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:*

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

[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 then is also welfare maximizing in terms of the number of active firms. However, if the expected profit of the marginal entrant is greater than this—e.g., equal to the average profit among the entrants—then the equilibrium is characterized by excessive entry.

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

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) $\tilde{p} = \bar{p}_0 > \bar{p}_1 > \cdots > \bar{p}_N > 0$;

(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 shows that the results obtained for N=2 generally hold. 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. Parts (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 the results in Gans and Stern (2000) showing that an incumbent behaves differently (invests less) in the face of entry—anticipating the opportunity to acquire a successful entrant—from 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 then 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 with 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 the 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 cannot 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 and Extensions

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. The Importance of Competition in the Market for Acquisitions

The fact that the acquisition price of an entrant depends on the difference in value from the second best technology is clearly essential for our results since 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:

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

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. Certainly in complex technology industries such as ICT and mechanical engineering it is generally relatively simple to invent around a patent. And even in discrete technologies such as drugs and chemicals the scope of patents is often too narrow to allow an innovator excluding competing technologies (see, e.g., Sternitzke 2013). More generally, our results point to the beneficial welfare effects of technology competition on ex-ante R&D choices, which provide an additional argument for optimal patents being narrow but sufficiently long-lived to provide firms with incentives to do R&D (Gilbert and Shapiro 1990).

5.2. 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 ≤ b ≤ 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 incumbent and entrants are driven by the difference in the value of having the second best technology rather than the specific form of the bargaining game.

5.3. 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. We will refer to firms with market access as "incumbents" but these could equally well be firms that are active in a neighboring market and that face a negligible entry cost. Hence, the analysis can be thought of as a comparative static exercise in which the (infinite) entry costs of the two entrants are removed successively.

The setup is as follows. First, all firms choose the success probability of their R&D project. After the R&D outcomes are realized, the incumbents compete to acquire the entrant (if an entrant exists and is successful). Finally, the incumbents compete in the product market.[7] The incumbent in possession of the best technology after the acquisition stage earns profit equal to the difference in value between the best and the second best technology. All other incumbents earn zero profits.

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

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[7] The assumption that the incumbents do not acquire each other can be justified by the presence of an antitrust authority that prohibits mergers and acquisitions that serve only to reduce competition and do not bring efficiency gains.

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 again reflects the value to 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 a profit. Notice also that our results are slightly stronger in the case of two incumbents and one entrant because 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 thus exists independent of how many firms have market access. However, our analysis shows that if there are entrants without direct market access, these tend to be the ones pursuing the more radical innovation projects in equilibrium.

5.4. Sequential Moves

Real-world R&D decisions are often best modeled as simultaneous moves as 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 analyzing the sequential-move game, we restrict ourselves to N=2. First, we analyze a game 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 $p_I \leq \overline{p}_I$:*

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

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 succeeds in developing an innovation because in these circumstances the incumbent earns $p_I\pi(p_I)$. 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 also for a game in which the incumbent moves first and then all entrants move simultaneously Proposition 6 holds.

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 whether the incumbent moves second or third (the case of *I* moving first is covered by Proposition 6).[8]

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.

5.5. 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

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[8] 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 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 movers; 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.

$\pi'(\phi_i) \geq 0$ 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.[9] The reason why no equilibrium exists in which an entrant invests more than the incumbent is again related to the 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.

The results in Propositions 1 and 7 contrast in an interesting way, and illustrate the challenges involved in testing empirically whether incumbents or entrants conduct 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 among 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 would a hypothetical social planner because it is not able to appropriate the full value of the entrants' technologies. This results

[9] 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 where at least one (success rate, technology value) is strictly better than those of the entrants.

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.[10] 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 into 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 three largest firms (Solid State Technology, 2010), and by a larger number of small firms entering the industry yearly which ultimately are either acquired 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; iSuppli, 2010; Solid State Technology, 2010). Industry turnover was more than $4 billion (bn) in 2009 (compare the total revenue of chip manufacturers of $230 bn). The industry grew on average 3% year on year until 2006 when growth slowed somewhat, 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 the 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

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10 A brief description of innovation in the EDA industry is also contained in Kleer and Wagner (2013).

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 derived partly from the extant literature (Henderson, 1993; Christensen and Bower, 1996) and partly from 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 in order to maximize the insights gained from succeeding interviews. From December 2005 to January 2008, eight interviews (10 interviewees) were carried out with senior professionals and scientists with detailed knowledge of the EDA industry. The list of interviewees comprises representatives from the two largest and some smaller EDA firms, industry consultants, and academics from America and Europe. Each interview lasted between 30 minutes and two hours. Three interviews were conducted over the phone or by email, the remainder were face to face. Interviews were subsequently transcribed and the written material was then analyzed. Two interviews were conducted in German, so interview quotes have been translated into English.[11]

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 dropped significantly and has still not fully recovered. Semiconductor firms tried to mitigate this reduction by

[11] Further details of each interview (date, duration, interviewee's function, type of organization employing the interviewee) are available from the authors upon request.

putting heavy pressure on suppliers, including those of EDA tools, to innovate in order to reduce cost. As a first stylized fact of the analysis, we note the continuously increasing requirements for EDA tools, and hence 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, the incumbents often fail to address these needs in a systematic manner, as illustrated by 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 better performing products. According to our interviewees, and illustrated by the above quote, these start-ups are frequently acquired by the larger incumbents. Such acquisitions, in turn, may trigger heightened acquisition efforts by competing incumbents in order to catch up.

As we argue below, the relative success of start-ups compared to incumbents derives partly from the fact that, unconstrained 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.*" This observation is in line with the work of Holmström (1989) who argues large firms introduce control and bureaucracy to minimize the cost of incentivizing production activities but in the process screen out more entrepreneurial individuals. As a stylized fact, we note that both, entrants and incumbents innovate but that incumbents often fail to develop a solution of satisfactory quality—or any solution at all—and in this case usually acquire start-ups.

6.5. Type of Innovation Pursued

It emerges from the interviews that entrants generally choose riskier innovation projects. Interviewees suggested a number of reasons for this. These in part relate to the obstacles identified in the literature on disruptive innovation (Christensen and Bower, 1996; Christensen, 1997), namely, that incumbents often are 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 shows: "*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 observation that large incumbents generally have a weak track record of developing new technologies in-house but are rather successful at further development of an existing project, i.e., at carrying out incremental innovation. On closer inspection, it is clear that not only does much of the innovation in the EDA industry emerge 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 project success. This was 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, i.e. they pursue innovation projects that are both more likely to fail, and in case of success, are more valuable than those pursued by incumbents.

6.6. 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 that entrants will be acquired and will become integrated into the design flow of one of the three large vendors, as succinctly described by one interviewee: *"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."*[12]

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 certainly are the most prevalent. This is partly because being acquired is financially attractive to start-ups since initial public offerings (IPOs) are less predictable, and also venture capitalists aiming for a profitable exit always consider the option of a trade sale. Several interviewees confirmed this view, stating that "*for most of these small companies' the 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 to 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,

[12] A start-up's innovation constituting a particular tool in the design flow is complementary to the existing other tools in this flow offered by incumbents. However, we found no indication of a complementary interaction between an incumbent's and a start-up's innovations. It is the substitutive relationship between innovations for the same type of tool that matters.

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—and almost always need to be—acquired, and that incumbents rely to some extent on this source of new technology.

Summarizing, the EDA industry fits both the assumptions made in our model and the key predictions derived from it, rather well. While there are several factors that influence the firms' R&D strategies, the fact that incumbents "*are relying on start-ups*" and on the possibility of acquisition clearly contributes to making entrants the predominant source of radical innovations in the EDA industry.

7. Discussion and Conclusion

New entrants to a market are characterized by various features, among them organizational flexibility, lack of established customer relationships, and the absence of existing products. All 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 is missing from this list. Defining entrants solely as firms that need to be acquired in order to commercialize their innovations, our model generates—based on a different mechanism to earlier studies—the familiar result that entrants are more likely to produce radical innovations. Essentially, the existence of a market for technology between entrants and incumbents drives the former to pursue 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 which, in case of success, will be more valuable. Furthermore, the higher the number of start-ups and the stronger the competition among them, the more valuable the most radical project pursued. Also, entrants pick projects with pairwise different success probabilities—a prediction of our model that differs from those of existing ones.

The qualitative empirical study of the EDA industry has confirmed that our model assumptions are realistic. The EDA industry is characterized by few incumbents and numerous start-ups. Both incumbents and start-ups perform R&D, but the latter generally 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' superiority in developing radical innovations also seem to apply to 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 focuses 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 these industries. Second, the pharmaceutical industry could also fit our framework. Here, smaller biotech firms supply new technologies and products to large pharmaceutical firms which then do the final testing and trials, go through the approval process, and commercialize the products. Also, Cabral (2003) cites evidence from the biotechnology industry where one of the two winners in the race for artificial human insulin was acquired. He shows also that the contestants chose approaches that differed in relation to their radicalness rather than their effort levels. The cases of Gilead acquiring Pharmasset (Bloomberg, 2011) and of Bristol-Meyers Squibb acquiring Inhibitex (Wall Street Journal, 2012), mentioned in the Introduction, provide further support for our results from the biotech industry.

Inevitably, 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 are not able to demonstrate the uniqueness of the equilibrium in full generality. Second, we provide a robustness check regarding the number of incumbents in Section 5.3 (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 the 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, if the probability of such an event is small enough, our model should be a good approximation. Still, generalizing our model along these dimensions is an interesting area for future research.

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 contributes important new aspects to this variegated picture.

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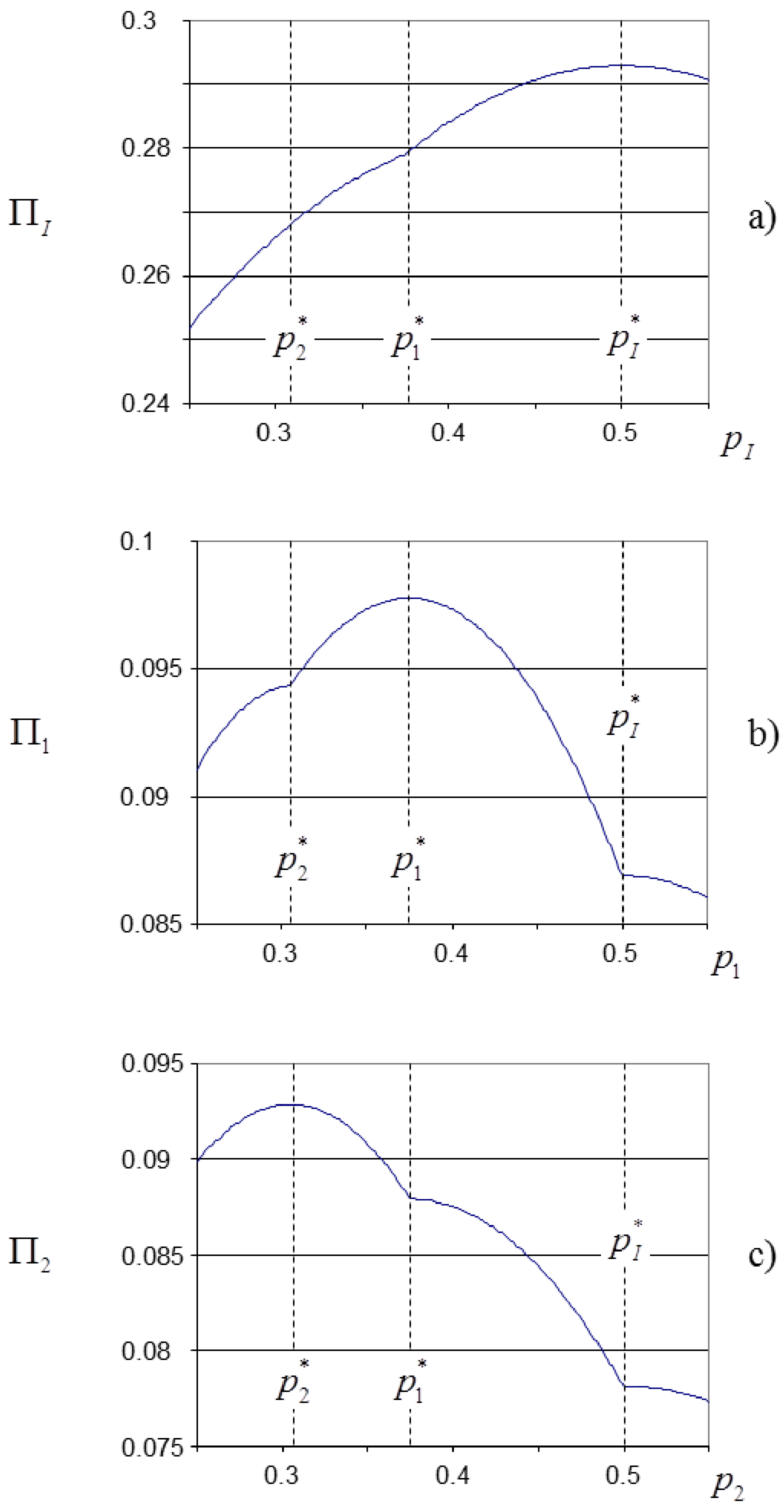
Figures

Figure 1 Firms' Payoffs when Deviating from Equilibrium, for N=2 and $\pi(p) = 1 - p$



Appendix

Proof of Lemma 2

Assume there is an equilibrium in which two or more firms pick 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 $\varepsilon > 0$):

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

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

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.

Again by induction we now show that $\bar{p}_k > 0$ and $h_k < [p\pi(p)]'_{p=0} \equiv \pi(0)$ for all k. It is true for the base case: $\bar{p}_0 = \tilde{p} > 0$, and $h_0 = 0$ by definition. Assume it is true for k-1. Then h_k is a weighted average of $\pi(\bar{p}_{k-1})$ and h_{k-1}, both of which are less than $\pi(0)$. Thus, also h_k is less than $\pi(0)$, from which $\bar{p}_k > 0$ follows because it is defined through the condition $[p\pi(p)]'_{p=\bar{p}_k} = h_k$.

Proof of Proposition 1

The proof proceeds as follows. First (a), starting from the assumption that $p_I > p_1 > \ldots > p_N$ 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 constitutes 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 $m < k$. This deviation changes the shape of k's profit function (since now there are m-1 other start-ups whose value in case of success is less than or equal to k's, as opposed to k-1 before the deviation), and as a result the applicable first-order condition becomes (10) with k replaced by m. Thus, when k deviates to some $p_k' \in [p_m^*, p_{m-1}^*]$, then the best it can do is to deviate to $\bar{p}_m$ (since by the FOC, this is the optimal choice of p_k' within this interval). We now show that even this 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. But due to the FOC, there can be no incentive to deviate from p_m^* to slightly larger values of p (since the optimal choice of p_k' in $[p_m^*, p_{m-1}^*]$ is p_m^*). Hence, there must be an incentive to deviate to slightly smaller values of p. That is, there exists some $p_k' \in [p_{m+1}^*, p_m^*)$ resulting in greater profit than $p_k' = p_m^*$. Applying this argument iteratively 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 $\{1, 2, \ldots, k\}$. 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 a 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 iteratively shows the incumbent has no incentive to deviate to some $p_I' \leq p_1^*$. Hence, $p_I^* = \bar{p}_0$ and $p_i^* = \bar{p}_i$ for $i = 1,\dots,N$ 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 $\Pi_I^* \geq \tilde{p}\pi(\tilde{p})$, 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, $\Pi_1^* < p_1^*\pi(p_1^*) < \tilde{p}\pi(\tilde{p}) \leq \Pi_I^*$, which completes the proof.

Proof of Proposition 2

Consider the candidate equilibrium with $p_1 > p_2 > \dots > p_N > p_I$. Define A as the expected value of the highest realized value among the entrants $1, \dots, N-1$, 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:

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

The resulting first-order conditions are:

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

Since $p\pi(p)$ is concave and increasing in p for $p < \tilde{p}$, 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 the roots for the 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, which 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 $p_2^* \le p_1^* \le p_I^*$. Then, the profit function of the incumbent can be written as:

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

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 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 (π_j) is greater than or equal to the realized value of incumbent i's project (π_i), $\pi_j \geq \pi_i$.*

(i) *If the realized value of the entrant's project (π_E) is greater than or equal to π_j, then incumbent j acquires the entrant at a price of $\pi_E - \pi_j$. The two incumbents compete in the market, and the profits of incumbent j and i are $\pi_j - \pi_i$ and 0, respectively.*

(ii) *If π_E is less than π_j but greater than or equal to π_i, then incumbent j acquires the entrant at a price of 0. The two incumbents compete in the market, and the profits of incumbent j and i are $\pi_j - \pi_i$ and 0, respectively.*

(iii) *If π_E is less than π_i, then no acquisition takes place. The two incumbents compete in the market, and the profits of incumbent j and i are $\pi_j - \pi_i$ and 0, respectively.*

Proof. Follows from standard Bertrand competition logic.

Using Lemma A.1, it is now possible to write down the expected profit of the firms as a function of the chosen success probabilities. Consider first a candidate equilibrium where $p_E^* \leq p_2^* \leq p_1^*$. The profit functions can be written as:

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

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

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

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 the 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 shows that the incumbents choose $p_1^* = \bar{p}_0$ and $p_2^* = \bar{p}_1$. The entrant also chooses $p_E^* = \bar{p}_1$ in the candidate equilibrium. However, it follows from the first part of the proof that this cannot constitute an equilibrium, because then there 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. *$p(\phi_i)\pi(\phi_i)$ is concave in ϕ_i, $c(\phi_i)$ is convex in ϕ_i, and $p(\phi_i)\pi(\phi_i) - c(\phi_i)$ 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, implying that $p(\phi_i)\,\pi(\phi_i)$ is strictly increasing in ϕ_i.*

Assumption 3.A. *$0 \leq p(\phi_i) < 1$ for all $\phi_i \geq 0$ 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, 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 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 $B1 > A1$ (due to Assumptions A.2 and A.3) and $B2 > 0$ (due to Assumption A.2). This, in turn, is less than the right-hand side of the first-order condition associated with entrant 1's problem, because $C1 > B1$ (due to Assumption A.1), $C2 > B2$ (due to Assumptions A.2 and A.3), and $C3 > 0$ (due to Assumptions A.2 and A.3). It follows from Assumption A.1 that $p(\phi_i)\pi(\phi_i) - c(\phi_i)$ is concave in ϕ_i. Hence, as the left-hand sides are decreasing in the R&D intensity ϕ_i, the first-order conditions imply that $\phi_I^* > \phi_2^* > \phi_1^*$ in equilibrium.

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, $\Pi_I(\phi_I', \phi_1^*, \phi_2^*)$ is increasing in ϕ_I' for all $\phi_2^* > \phi_I' \geq \phi_1^*$. Also, as the incumbent's profit function is continuous at $\phi_2^* = \phi_I'$, it follows from the analysis that $\phi_I^* = \phi_I'$ gives rise to higher profit for the incumbent than any ϕ_I' such that $\phi_2^* > \phi_I' \geq \phi_1^*$.

Consider instead a deviation to some $\phi_1^* > \phi_I'$. 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 ϕ_I' for all $\phi_1^* > \phi_I'$. Also, 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 $\phi_2^* > \phi_I^* \geq \phi_1^*$.The profit functions of I and 2 are then:

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

The corresponding first-order conditions are:

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

Arguing as above, the right-hand side of the first-order condition associated with 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 $\phi_2^* > \phi_I^* \geq \phi_1^*$. It can be shown in a similar manner that there does not exist an equilibrium in which $\phi_2^* \geq \phi_1 > \phi_I^*$.