Competition and the Efficiency of Markets for Technology*

Marie-Laure Allain[†] Emeric Henry[‡] and Margaret Kyle[§]

July 1, 2013

Abstract

The sale of R&D projects through licensing facilitates the division of labor between research and development activities. This vertical specialization can improve the overall efficiency of the innovative process. However, these gains depend on the timing of the sale: the buyer of an R&D project should assume development at the stage at which he has an efficiency advantage. We show that in an environment where the seller is overconfident about the value of the project, she may delay the sale to the more efficient firm in order to provide verifiable information about its quality, though this delay implies higher total development costs for the project. We obtain a condition for the equilibrium timing of licensing and examine how factors such as the intensity of competition between potential buyers influence it. We show that a wide array of different explanations, based on differences in information, beliefs or risk profiles, lead to the same qualitative results. We present empirical evidence from pharmaceutical licensing contracts that is consistent with our theoretical predictions.

1 Introduction

Specialization in different phases of the innovative process is increasingly common in many industries, such as the pharmaceutical, chemical and semiconductor sectors (Arora et al. (2001)). This division of labor, facilitated by the growth of licensing markets that allow for sale of projects, potentially improves the efficiency of the innovative process. We argue in this paper that these efficiency gains crucially depend on the timing of exchange, by which we mean the phase of development at which the R&D project is transferred from one firm to another. Consider two firms, one more efficient in conducting early stage research and the other more efficient in the final stage of product development. It is socially optimal to have the relatively efficient firm own the project at each

*Henry thanks the support of the Agence Nationale de la Recherche through its program Chaire d'excellence junior. Kyle thanks Pfizer Inc. for research center support to IDEI.

[†]Ecole Polytechnique and CNRS, marie-laure.allain@polytechnique.edu

[‡]Sciences Po Paris and CEPR, emeric.henry@sciences-po.fr

[§]Toulouse School of Economics, IDEI and CEPR, (margaret.kyle@tse-fr.eu

stage, i.e. to transfer the project to the second firm at the end of the initial stage. A delay in this transfer increases the total cost of innovating, and might lead to the innovation being abandoned. Thus, the timing of technology transfer is an important determinant of the innovation rate. We identify factors that may distort the timing of the transfer and reduce the productivity of R&D in a theoretical model, and provide empirical evidence consistent with the predictions. In particular, we explore the relationship between market structure and the efficiency of markets for projects.

We explore several potential reasons that can generate delays in technology transfers. In the main model, we consider the case where the seller is more confident than the buyers about the prospects of the project. In this case, even though development is more costly for her, the seller might want to delay the sale to allow for information to be revealed on the quality of the project, since she is confident that the information will be in her favor. We show that in general, there is a large number of explanations generating similar dynamics: the seller might be better informed about the quality of the project or about some characteristic of the market, such as the number of buyers competing for the purchase. There might also be differences in risk profiles between them. All these different explanations will lead to the same qualitative results that we explain below.

We describe the baseline model based on overconfidence of the seller. We consider one innovator and n potential buyers who compete on a downstream market. Prior to the first period, the innovator has obtained a project that requires additional development to be brought to market. While she faces some positive cost of development, development is costless for the buyers. It is thus socially optimal to transfer the project from the innovator to one of the buyers in the first period. In the first period, the value of the project is uncertain and the seller places a higher probability that it is good than the buyers. Furthermore, development efforts from the first to the second period reveal verifiable information that resolves all uncertainties about values.

We identify a necessary and sufficient condition for efficient transfer of the project in the first period. The key tradeoff is the following: because the price of the project in the first period incorporates buyers' uncertainty about its quality, the innovator, who is more confident that her project is good, is tempted to wait for information about the project's value to be revealed, at which point she obtains a price that reflects its true quality. However, she must incur development costs to provide such information. An agreement can therefore be reached in the first period only if the efficiency advantage of buyers in the development stage is large enough compared to the overconfidence difference between the seller and the buyers.

We find the result that when profits on the downstream market do not depend on the number of buyers n, an increase in the number of buyers unambiguously delays the transfer. That is, counter to the usual intuition on the positive role of competition, increased competition leads to increased inefficiency in the market for projects. This is because an increase in n increases the bargaining power of the innovator and the price she can negotiate in the second period. This increase is of course valuable only if the project is good. Since the innovator is more confident that this is indeed

the case, she is therefore more inclined to wait when n is large.

When profits on the downstream market also depend on n, an increase in the number of buyers has two countervailing effects on the second period price: it increases the bargaining power of the innovator, but it also decreases the downstream profits obtained from the innovation. That is, the innovator obtains a larger slice of a smaller pie. In this case, we identify a condition such that increased competition leads to earlier signing.

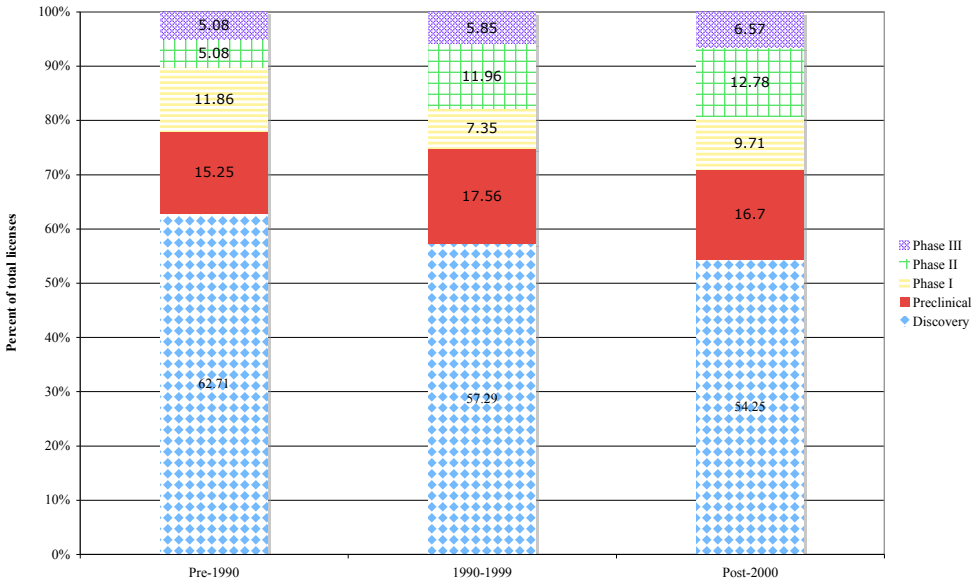
We also study a variant of the model in which we distinguish two types of potential buyers: incumbents with existing products on the market and potential entrants without any stake. While additional entrants affect competition for the innovation, the downstream profits an entrant realizes from signing depend only on the number of incumbents. We show theoretically that delay in the transfer is increasing in the number of entrants and typically decreasing in the number of incumbents. This model will be the core of our empirical analysis.

As stated earlier, we find similar results for a wide variety of models discussed in section 4, assuming various types of differences between the seller and the buyers. Most of them (except differences in risk profiles) are based on the fact that information is revealed during the process and that there are differences in information or beliefs. It is thus natural to think that the inefficiencies we identify should be overcome using milestone payments. We find in the data that the use of milestone payments is very limited and we develop a model, based on moral hazard concerns, that provides a potential explanation and shows that inefficient delays may still exist with milestone payments.

Our empirical analysis of licensing contracts in the pharmaceutical industry is consistent with our theoretical predictions. This industry is a very good illustration of the process we described. There is increasing division of innovative labor between small biotechnology firms and large pharmaceutical companies. For instance, Angell (2004) claims that one third of the drugs marketed by major pharmaceutical companies originate from licenses with biotechs or universities. Biotechnology companies seem to have a comparative advantage in achieving early stage discoveries, while large pharmaceutical firms are considered more efficient in conducting later stage clinical testing. We argue that biotechnology firms are initially better informed about the quality of their drug candidates. However, verifiable information is revealed during the clinical trials that are required for regulatory approval. Once a clinical trial phase is successfully completed, the information asymmetry shrinks and potential buyers of a license become more confident of the drug candidate's value.

Figure 1 illustrates that in this industry, the fraction of licensing contracts signed after the discovery and preclinical stages has increased by more than 30% since 1990, a period also characterized by low numbers of new drugs launched. This delay in technology transfer also coincides with a period of increased market concentration, as the pharmaceutical industry has experienced substantial merger activity. This justifies our particular focus on the link between the number of

Figure 1: Stage at licensing signing over time



potential buyers and the timing of technology transfer.

We combine data on licensing deals and the stage of drug development at signing with data on downstream competitors, who compete on the product market as well as for the license. Controlling for various measures of financial constraints and other factors, we provide empirical evidence that is consistent with our theoretical prediction for the relationship between competition and licensing delay, though we do not attempt to establish a causal link. We also test the variant of the theoretical model that distinguishes entrants from incumbents and again confirm the predictions of the theoretical model across a range of specifications to evaluate robustness. We find that the percentage change in the probability of late signing for a one-percent increase in the number of incumbents is -0.31, and the corresponding figure for entrants is 0.17.

There is a large literature that examines different aspects of licensing contracts, such as the choice between fixed fees and royalty rates, allocation of control rights, both theoretically and empirically (Lerner & Merges (1998), Lerner & Malmendier (2005), Kamien & Tauman (1986), Beggs (1992) and Choi (2001)).[1] However, with the exception of Gans et al. (2008) and Luo (2011), the timing of licensing has been ignored. Gans et al. (2008) describe several reasons for deviations from

[1]See also Anand & Khanna (2000), Vishwasrao (2006), Mendi (2005), and Higgins (2007).

the socially optimal timing of technology transfer, including search costs, asymmetry of information and uncertain property rights. They show that the resolution of uncertainty over the scope of intellectual property (specifically, a clarification of the claims granted to a patent) speeds licensing. Like Luo (2011), we focus on the asymmetry of information between buyer and seller as the key friction in the market for projects, but we also examine the impact of market structure on timing.

We also show that assuming asymmetric information between seller and buyers, leads to similar results. Much of the existing literature on technology transfers under asymmetric information focuses on the case of weak or nonexistent intellectual property rights. In particular, Anton & Yao (2002) examine the problem of an innovator revealing some information to convince a potential buyer of the quality of her product under the risk that the buyer can then fully appropriate the invention without any form of payments. We concentrate here on a different aspect. Property rights do exist, but in order to convince a buyer of the project's value, the innovator is forced to incur development costs even when she has no comparative advantage in development.

Daley and Green (2011) consider a related issue: a seller is better informed than the potential buyers about the value of the asset he wants to sell. At each point in time, he receives offers from the buyers, and can accept of reject these offers. Information about the value of the asset is gradually revealed to the buyers: the information asymmetry is thus reduced over time. This reduction in information asymmetry has an ambiguous effect on the market efficiency: depending on the buyers' priors about the quality of the asset, information can either foster or reduce inefficient delays in trade. Our setting differs from theirs along several dimensions. First, we focus on the role of competition among the buyers, and in particular we consider the impact of competition on buyer's outside options, while they model the "market" as a set of short-lived buyers (they die at each period and new buyers enter) with no strategic interactions. Furthermore, while they consider a perfectly informed seller, ours can be imperfectly informed as well.

The remainder of the paper is organized as follows. In Section 2 we introduce the baseline model. In Section 3 we present the results on the timing of the transfer and discuss the effect of market structure. In section 4, we show that a large class of models leads to the same qualitative results. We then present empirical evidence coherent with our predictions: in section 5 we present data an estimation approach and in section 6 we present the results. All the proofs can be found in the appendix.

2 Model

We consider a model with one innovator holding a pre-existing project and facing $n \geq 2$ other firms. These n firms are the only potential buyers of the project, and do not themselves attempt to innovate (for instance, because their cost of early stage innovation is very high). The project is sold by running an auction described below. We consider only exclusive transfers that grant the full ownership of the innovation to the buyer.

The game has two periods that differ from each other in two important ways. First, at the end of the first period, if the innovator has not sold the innovation, she needs to decide whether to develop the product further. The potential buyers are assumed to be more efficient in development. Development of the innovation from period 1 to period 2 costs Δ for the innovator and zero for the buyers. Second, period 1 is characterized by uncertainty about the value of the innovation. The innovator believes the product is good with probability p while the potential buyers believe it is good with probability q. We assume that the innovator is overconfident about the value of the innovation, i.e. $p > q$ (see Hayward et al. (2006), Galasso & Simcoe (2011), Malmendier & Tate (2005), for a discussion of overconfidence). At the beginning of the second period, the value of the innovation is revealed as a result of the verifiable evidence generated during the development process, if development is pursued.

If the project is bad, we assume that it does not generate any profits. The profits obtained from a good innovation are given by:

- $\pi_0(n)$ is the profit of a buyer if neither he nor any of his competitors sign a license.
- $\pi_l(n)$ is the profit of a buyer if one of his competitors signs a license.
- $\pi(n)$ is the profit of a buyer if he signs a license.

We assume $\pi(n) \geq \pi_0(n) \geq \pi_l(n) > 0$. Each buyer wants to buy a good project, but should he fail to do so, he prefers that no rival buys it either. We assume that all profit functions are weakly decreasing in n and are continuously differentiable.

Buyers are heterogeneous. There is a fixed cost of production c that is drawn for each buyer from a uniform distribution with support $[0, \bar{c}]$. The fixed cost must be incurred after observing the value of the invention (it will be paid only if the project is good). Specifically, the value to a buyer of a bad project is 0, but $\pi(n) - c$ if the project is good.

The project is sold through a second price auction. The seller initially decides whether to run the auction in the first period or pay the development cost Δ and wait for the second period to conduct the auction. Note that Δ must be paid before the innovator learns the type of the project.[2] Note that we obtain qualitatively equivalent results if we model the sale as a sequential bilateral negotiation over fixed price contracts, rather than an auction Allain et al. (2011).

3 The timing of the sale of a project

In our model, it is socially optimal to transfer the project from the innovator to the buyer in the first period, as development is costless for buyers. We show that overconfidence on the innovator's side can systematically delay the sale. Furthermore, market structure affects the timing of the transfer.

[2]Equivalently, the innovator could run an auction with a reservation price in the first period.

3.1 Equilibrium strategies

We start by characterizing the equilibrium strategies. We first show that the unique bidding strategy for the buyers in both periods is to bid their expected value for the good, a standard result in second price auctions.

Lemma 1 *In the second period, if the innovation is good, buyer i with cost c_i bids $\pi(n)-\pi_l(n)-c_i$. In the first period, if an auction is run, buyer i with cost c_i bids $q(\pi(n)-\pi_l(n)-c_i)$.*

Using the result of Lemma 1, we can derive the payoff the innovator can expect from running an auction in the first or in the second period. If she runs it in the first period she expects a payoff equal to the expected value of the second highest bid:

$$q\left(\pi(n)-\pi_l(n)-E[c_{n2}]\right) \tag{1}$$

where $E[c_{n2}]$ is the expected value of the second lowest cost among the costs of the n bidders.

If she waits for the second period (and thus pays the development cost Δ), she expects a payoff of:

$$p\left(\pi(n)-\pi_l(n)-E[c_{n2}]\right)-\Delta \tag{2}$$

This naturally leads to our first result:

Proposition 1 *The unique Subgame Perfect Equilibrium is such that the project is sold in the first period if and only if:*

$$\Delta \geq (p-q)\left(\pi(n)-\pi_l(n)-E[c_{n2}]\right) \tag{3}$$

As overconfidence $p-q$ grows, it becomes more likely that the license is signed in the second period.

If this condition is satisfied, the socially optimal timing of licensing is achieved: the project is sold in the first period and the more efficient buyer develops the innovation. However, if the innovator is much more confident than the buyers of the prospects for the project or if the efficiency difference Δ between the innovator and the buyers is small, the threshold for early signature is more difficult to meet and late (and inefficient) signature is more likely. The condition of Proposition 1 can be re-expressed as follows: a license is signed in the first period if and only if the cost of development for the innovator is sufficiently large: $\Delta \geq \underline{\Delta}(n)$, where

$$\underline{\Delta}(n) \equiv (p-q)\left(\pi(n)-\pi_l(n)-E[c_{n2}]\right). \tag{4}$$

In practice, deals vary in terms of the efficiency and overconfidence differences between the seller and the buyers, so that some will satisfy the condition and reach an early agreement, while others will delay. This tradeoff is relevant in practice if we are in the parameter space where Δ is close to

$\underline{\Delta}(n)$. To the best of our knowledge, no precise data exist on Δ or $p-q$ to make this judgement. However, two facts lead us to believe that the tradeoff should be relevant in practice. First, we show that the effect of the number of firms n on timing of the transfer, which we will derive below and follows from this condition, is present in the data. Second, we expect a positive correlation between Δ and $p-q$: inexperienced biotechs will tend to have higher costs of conducting the trials and to be more overconfident. This correlation makes it more likely that we stay at the frontier where Δ is close to $\underline{\Delta}(n)$ when we study a diverse set of firms.

3.2 The effect of market structure

We now investigate how the number of buyers in the market n affects the condition of Proposition 1 and thus the timing of licensing. Specifically, we examine how $\underline{\Delta}(n)$, which we call the efficiency threshold, varies with n. If $\underline{\Delta}(n)$ increases with n, delays in licensing become more likely as the number of competitors increases.

3.2.1 Profits do not depend on n

The number of buyers may influence both the likelihood each individual player wins the auction (it directly changes the number of bidders) but also the downstream profits. As a benchmark, we begin with the case where the profits (π_l, π_0, π) do not depend on n. For example, an additional competitor may not affect profits if innovations are purely market expanding and have no business stealing effect. This case isolates the effect of n, the number of firms competing for the license, on the price the innovator can extract. The following proposition states that the effect of n on the timing of licensing is unambiguous in this case.

Proposition 2 *If the payoffs on the market do not depend on n, the efficiency threshold increases with n: the condition for early licensing is harder to meet as the number of buyers increases.*

This result is intuitive. As n increases, the price the innovator can obtain in the auction increases. Indeed, the expected value of the second lowest cost $E[c_{n2}]$ decreases mechanically as more draws are taken from the distribution. Due to her overconfidence, the innovator perceives higher benefits from waiting, while the cost Δ remains unchanged. Thus, overall, an increase in n will delay signature.

3.2.2 Profits depend on n

When the profits depend on n, the effect of a change in the number of competitors is more subtle. There are two countervailing effects of n on the price the innovator can extract. On the one hand, it raises the bargaining power of the innovator since there is a higher chance that one bidder has a low implementation cost c. On the other hand, it decreases the actual profits derived from the

innovation, since profits are a decreasing function of n. The tension between these two effects yields an ambiguous effect of n on the price in the auction and thus on the timing of licensing.

To obtain precise predictions, more structure needs to be imposed. We assume that profits decrease with n and are positive, a natural assumption in most models of competition. We then obtain the following result:

Proposition 3 *If $\pi^{'}(n) - \pi_l^{'}(n) < \frac{-2\overline{c}}{n+1}$, then the efficiency threshold decreases in n: the condition for early licensing is easier to meet as the number of buyers increases.*

The intuition of this result is the following. There are now two effects of an increase in n. First, the value of second lowest bid increases because more draws of c_i are taken. Given our assumption that the costs are uniformly distributed, the speed at which $E[c_{n2}]$ decreases is given by $\frac{2\overline{c}}{n+1}$. Second, the profits that the bidders expect decrease with n at a speed $\pi^{'}(n) - \pi_l^{'}(n)$, and so the expected profits decrease for the seller as well. If the second effect dominates, early licensing becomes more likely, since the seller has less incentive to wait. We show in the Appendix that this condition is satisfied for a standard model of Bertrand competition with product differentiation where the innovator introduces a new variety of product on the market.

3.2.3 Entrants and incumbents

Our previous analysis assumed that all potential buyers were identical except in their implementation cost. In reality, of course, the value of the project may differ across buyers for many other reasons. In this section, we allow for an additional source of buyer heterogeneity, focusing on what we view as a key difference between them: some potential buyers are active in the same class as the licensed innovation, while others aren't. Formally, we assume that there are n "incumbents" denoted by $i \in \{1, ..., n\}$ and e potential "entrants" denoted by $j \in \{1, ..., e\}$.[3] Each entrant has a fixed cost of production drawn from the same distribution as the incumbents' costs, and the same prior beliefs about the quality of the project. Entrants are not currently active on the downstream market and get profits $\pi_e(n+1)$ (which depend on n, but not on e) from buying the drug. Since they have no current stake on the market, they receive zero if they fail to buy it. In contrast, an incumbent receives $\pi(n)$ if he buys the license, $\pi_l(n+1)$ if an entrant does and $\pi_l(n)$ if another incumbent buys the license. In this context, we obtain the following result:

Proposition 4 *All Perfect Bayesian Nash Equilibria in pure strategies have the following properties:*

1. *The efficiency threshold weakly increases with the number of entrants e (the condition for early licensing is more difficult to meet).*

[3] In the empirical section, we define entrants as firms with drugs in a larger related class but not the focal class, and incumbents as those already producing in the particular class.

2. *If $\pi_e(n+1) - \overline{c} \geq \pi(n) - \pi_l(n+1)$, the efficiency threshold decreases with n (the condition for early signing is easier to meet).*

Proposition 4 puts together the two cases discussed in sections 3.2.1 and 3.2.2, and is the core of our empirical analysis. The first result states that an increase in e unambiguously delays licensing. This is in essence a reformulation of Proposition 2. An increase in e has no effect on the profits of the winner, but has a direct positive effect on the winning bid since it increases the number of bidders and means that more draws from the cost distribution are taken.

The second result corresponds to the case considered in section 3.2.2, since n affects both the number of bidders and the expected profits on the market. The condition $\pi_e(n+1) - \overline{c} \geq \pi(n) - \pi_l(n+1)$ guarantees that an entrant necessarily wins the auction[4] and therefore implies that the only effect of n is to decrease the profits on the market. Note that we can impose a weaker condition (in the spirit of Proposition 3, for instance), but this formulation clearly highlights the main forces at play.

3.3 Milestone payments

One obvious solution to solve the issue of inefficient timing of the transfer of an project is to sign the contract in the first period based on a milestone payment that will be paid if and only if the project turns out to be good. In this environment, without any kind of friction, the project should always be transferred in the first period. However, less than 30% of the subset of licenses signed between 1990 and 2011 for which we have some information on contract details included milestone payments. Over time, this share has been relatively stable.

One natural explanation for the fact that milestone payment contracts are not widely used is moral hazard. It is not possible to contract on everything: in the case of pharmaceuticals, it is typically possible to contract on the results of the clinical trials but not necessarily on other dimensions, such as development or marketing efforts. We show that in such situations, the seller might still prefer to wait if he believes the buyers will not exert adequate effort.

We capture these concerns in the following modified version of our model. Suppose that the final value of the product if it is good depends on the level of development effort exerted by its owner (the bad quality drug still generates zero profits, irrespective of the effort). Specifically, if the innovator does the development from period 1 to period 2 and pays development cost Δ_H (resp. 0), the profits derived from a good innovation will be π_H (resp. π_L). The buyers still have an advantage in development. They can develop a product of quality π_H at cost $\xi_H < \Delta_H$, or obtain π_L for a zero cost of development. It is assumed that the milestone contracts can depend on the state, good or bad, but not on the level of profits when the state is good, i.e the parties can not contract on the level of $\pi \in \{\pi_L, \pi_H)$.

[4]Even if he has the highest possible draw for the cost, an entrant still obtains a higher value from buying the project than any incumbent

The innovator chooses to either develop the product herself until the second period or to run an auction in the first period, in which the buyers bid on a milestone-only contract. That is, the winner of the auction pays his bid only if the project is good. In this situation, if the innovator develops the product herself, she will exert high effort if:

$$p\pi_H - \Delta_H > p\pi_L$$

On the other hand, there is the possibility of moral hazard. For a given bid, the buyer will exert low effort if

$$q\pi_H - \xi_H < q\pi_L$$

So there is a parameter region where a tradeoff exists: if she does the development, the innovator incurs a higher cost but obtains a higher value innovation, while if she runs an auction with a milestone-only contract, the buyer will exert low effort. Overall, we have the following result.

Proposition 5 *The innovator exerts high effort while a buyer exerts low effort if and only if:*

$$\frac{\Delta_H}{p} < \pi_H - \pi_L < \frac{\xi_H}{q} \tag{5}$$

Furthermore, if this condition is satisfied, the license is signed in the second period.

Note that the difference in beliefs p and q is still key to our argument. We need to have a significant gap between the two beliefs to have signature in the second period. Indeed, it is the fact that the seller is overconfident about the value of the project that pushes her to invest more in development than the buyers. If they had the same belief, given that the buyers are more efficient in development, they would exert a higher development effort than the seller.

4 A robust effect of the number of buyers

4.1 The common thread

In this section, we consider a series of very different models, some based on asymmetric information between the seller and the buyers, others on differences in risk profiles. We find the striking result that all these different models reach the same conclusion as our benchmark model: a sale occurs in the first period if and only if $\Delta \geq \alpha r_2(n)$, where

$$r_2(n) \equiv (\pi(n) - \pi_l(n) - E[c_{n2}]) \tag{6}$$

is the revenue the seller can expect if the auction is run in the second period. The factor that varies across the different models is the value of α (for instance $\alpha = (p - q)$ in the baseline model). Since

we will show that α is independent of n, the effect of the number of buyers on timing of sale is the same as that described in section 3.2.

The important feature that all these models have in common is that there are two periods and in the second period, all uncertainty is resolved. The condition then reflects the tradeoff faced by the innovator: pay the extra development cost in the hope of extracting a higher revenue, proportional to the second period revenue or sell the project immediately.

4.2 Asymmetric information about value

We first consider the case where the innovator is better informed about the value of the innovation. We suppose the seller is perfectly informed of the value, while in period 1, the potential buyers believe that it is good with probability q and bad with probability $1-q$. The quality of the innovation is revealed at the beginning of period 2. The payoffs are otherwise the same as in the main model and the innovator sells the good by running a second price auction.

This asymmetric information can be due to the fact that the innovator has greater familiarity with her own project and its performance in laboratory experiments than would a potential buyer. Indeed, asymmetric information is well-understood to be a characteristic of markets for technology (Arrow (1971), Arora et al. (2001), Anton & Yao (2002)), and a number of empirical papers have focused on how to address it. For example, Hegde (2013) examines how contracts are structured (e.g., milestone payments and royalties) in biomedical licensing when "tacit" knowledge or asymmetric information is important. Wuyts & Dutta (2008) show that social networks may reduce the problem of information asymmetries, and Danzon et al. (2005) stress the importance of experience as demonstrable evidence of an innovator's quality. There is also compelling evidence from the Licensing Foundation's annual surveys of practitioners, in which 45% of the respondants are in health-related fields. As Cockburn (2007) reports in his analysis of this survey data, "[t]hese results suggest severe problems with inadequate data and asymmetric information....The critical role of ex ante imperfect or asymmetric information is also indicated by the high rates at which respondents cite revelation of new information about the end-user market or the performance of the technology as reasons to revisit contract terms" (p. 10-11).

In such an environment, if in equilibrium the seller with a good type innovation sells in the first period, she can only extract profits $q(\pi(n)-\pi_l(n)-E[c_{n2}])$, since the buyer is unsure of the quality of the drug. A seller who knows it has a good compound has an incentive to wait until the second period for the quality to be revealed. However, waiting is costly since the higher development cost Δ needs to be paid. The condition in the following proposition reflects this tradeoff:

Proposition 6 *An innovator with a good project runs an auction, and thus sells the project, in the first period if and only if*

$$\Delta \geq (1-q)(\pi(n)-\pi_l(n)-E[c_{n2}])$$

4.3 Low type with valuable idea

Here we keep the asymmetric information framework developed in the previous subsection, and we relax the assumption that a bad project has a zero value. We now assume that the profit obtained from a good innovation is π_H while that from a bad innovation is π_L. Furthermore, we assume that $\pi_L - \pi_0 \geq 0$, so that in period 2 a license will be signed with both types. We also assume that π_l is independent of the value of the innovation, which simplifies the calculations without affecting the results. In the second period, the types are revealed as before.

Proposition 7 *In equilibrium,*

1. *the low type always runs an auction in the first period;*
2. *the high type runs an auction in the second period if* $\Delta \geq (\pi_H - \pi_L)(1-q)$*, and otherwise the high type runs an auction in the first period.*

A pooling equilibrium where both types run an auction in the first period exists if Δ is high. Otherwise, there exists a separating equilibrium where only a bad type runs an auction in the first period, while the good type prefers to delay the sale in order to reveal its type. Note that if the bad type has a valuable idea, then it is always sold in equilibrium.

4.4 Asymmetric information about the number of buyers

The source of the asymmetric information between the seller and the buyers could be of a different nature. Arora & Gambardella (2010) suggests there is uncertainty about the transaction process, and the seller might be better informed about it than the buyers. For instance, the seller might directly observe the number of buyers interested in her project, while the buyers are uncertain about the number of competitors they face.[5]

To capture this idea, we consider the following model where there is no uncertainty about the quality of the project (everyone knows it is good), but there is asymmetric information about the number of buyers. The seller knows the number of buyers, but each buyer believes that he is the only one with probability p, or that there are a total of n buyers with probability $1-p$. In period 2, this information is revealed.

This is a signalling game in which the decision of whether or not to run an auction in the first period conveys the innovator's information about the number of buyers. In particular, if the seller knows there is a single buyer, she will always run an auction in the first period since she cannot extract any revenue in the second. The timing of licensing will be determined by whether there exists a separating equilibrium in which, if she observes there are n buyers, the seller waits for period 2.

[5] We thank an anonymous referee for this suggestion.

Proposition 8 *There exists an equilibrium such that an innovator who knows there are n buyers runs an auction, and thus sells the project, in the second period if*

$$\Delta \leq (\pi(n) - \pi_l(n) - E[c_{n2}])$$

The seller knows that if there are n buyers, she can extract revenues $\pi(n) - \pi_l(n) - E[c_{n2}]$ in period 2, since the buyers bid their values. A separating equilibrium exists as long as this value is greater than the cost of development.

Arora & Gambardella (2010) mention another potentially important idea. They cite a senior executive of a leading pharmaceutical firm who mentioned the winner's curse as a potential hurdle to transactions in markets for technology. In a scenario like this, the buyers all have private information about the value of the project, and underbid to avoid the winner's curse. The seller might then want to delay the sale so that information can be revealed. This provides an alternative explanation for delay, although the role of n in the timing of sale is unclear.

4.5 Differences in risk profiles

We examine a final possibility that yields a similar effect of the number of buyers on timing. Suppose the key difference between buyers and sellers is their risk profiles. In particular, we assume that both the seller and the buyers share the same belief about the prospect of the project (it is good with probability q), but differ in the way they discount payments obtained in the second period:[6] the discount factor of the seller is δ_s, while the buyers share a common discount factor δ_b. In this case we obtain the following result:

Proposition 9 *An innovator with a good project runs an auction, and thus sells the project, in the first period if and only if*

$$\Delta \geq (\delta_s - \delta_b)(\pi(n) - \pi_l(n) - E[c_{n2}])$$

Proposition 9 yields a similar condition as in our baseline case, except that the potential benefits do not come from a difference in beliefs about the quality of the project, but rather from a difference in risk profiles. However, a tradeoff only exists if $\delta_s > \delta_b$, which is unlikely to be the case if the biotech is the seller and the big pharma firms are the buyers.

Thus far, we have made no mention of real options, now a widely adopted approach to internal R&D management. The decision to develop a project from one phase to the next can be treated as the purchase of an option. In this framework, the "sell side" is usually ignored, while it is an integral feature of our model. In our context, a license contract involving an upfront payment with development milestones could also be interpreted as the sale of an option on the technology.

[6] We have ignored discounting thus far.

In a study of technology licensing contracts involving University of California inventions, Ziedonis (2007) found that option contracts (rather than immediate licensing) were more likely to be used when uncertainty about the underlying technology was high. The most likely purchasers of option contracts in his study were firms better able to assess the technology. In addition, purchasers able to absorb the knowledge underlying the technology had reduced incentives to license it after buying the option. These results highlight both the potential for asymmetric information (as completely uninformed firms are less likely to participate in the market for technology) and moral hazard.

Ziedonis (2007) notes that competition for a project might increase the cost of delay, i.e. decrease the value of an early-stage option. Our model has slightly more subtle predictions for the effect of competition, but is not inconsistent with the overall real options approach.

5 Bargaining with asymmetric information

In this section, we further investigate the robustness of the theoretical result by assuming that the project is sold through a bargaining process instead of an auction. Consider that the project can be transferred by signing a fixed price contract, determined by a bargaining process that we describe below. To keep things tractable, we assume that the innovator knows the value of its project. Once a contract is signed, the game ends: we consider only exclusive transfers that grant the full ownership of the innovation to the buyer. The cost of production c is now zero: all potential buyers are identical. If the quality of the innovation is known to be high, there are gains from trade between the innovator and any buyer: if a license is sold, the aggregate profits of the two negotiators, $\pi(n)$, are larger than their aggregate profit without sale, $\pi_0(n)$.[7]

5.1 A sequential bargaining framework

Bargaining between the innovator and the buyers takes place as follows. All buyers are randomly ordered in a sequence. The innovator negotiates one by one with each buyer. We call each bilateral negotiation between the innovator and an individual buyer a bargaining session. If bargaining breaks down with the current buyer, the innovator starts a bargaining session with the next buyer in the sequence. If bargaining succeeds, the game ends since licenses are exclusive.

As previously described, our model has two periods. If bargaining is unsuccessful with all buyers in the first period, the innovator must wait for the second period to start another sequence of negotiations. The order of bargaining is the same in the second period.[8] If all bargaining sessions fail, the players obtain their outside options. Within a period, the innovator cannot restart

[7] Note that we assume that the outside option of an innovator who has developed a good type innovation until the second period and has not sold a license is zero: introducing a positive outside option would not qualitatively alter our results (proof available upon request).

[8] Redrawing the order across periods does not qualitatively affect our results but complicates the exposition: proof available upon request.

negotiations with a buyer with whom bargaining previously broke down. To summarize, each period involves at most n bargaining sessions, and the game overall contains at most $2n$ sessions.

The bilateral bargaining procedure inside a session is as follows. We assume that with probability ϵ, a bargaining session does not start. That is, a breakdown can occur even before the start of a session.[9] With probability $1-\epsilon$, Nature draws one of the two players (each of them with probability 1/2). The selected player then makes a take-it-or-leave-it offer to his partner. If the offer is accepted, the game terminates. If it is rejected, the bargaining session ends, and the innovator starts a new bargaining session with the next buyer in the sequence (if any).

The information structure is as follows. The innovator knows the value of its project, but the buyers don't. All n-buyers share the same prior that the innovation is good with probability q. All players know n, and buyers know their positions in the sequence. However, the buyers cannot observe the negotiations between the other buyers and the innovator. In particular, following breakdown of a negotiation between the innovator and a particular buyer, buyers positioned later in the sequence do not know the offers that were made and do not even know if a session ever started with that buyer.

We focus on perfect bayesian equilibria in pure strategies. We solve the game by backward induction. All the results are limit results as the probability of exogenous bargaining breakdown ϵ converges to zero.

5.2 The bargaining game

5.2.1 Bargaining in the second period

At the beginning of the second period, the type of the innovator's idea is known to all. If it is bad, no license is signed. The description that follows therefore focuses on the case where the innovation is good. The following Proposition states that an agreement is reached with the first buyer in the sequence, and shows that the price of the license is increasing in n: a larger number of buyers in the sequence allows the innovator to extract a larger share of the surplus.

Proposition 10 *If the innovation is good and bargaining failed in the first period, a license is sold in the second period to the first buyer in the sequence.*

- *If the seller makes the offer, the price is* $p_{2S}^1 = \pi(n) - \pi_l(n)$;
- *If the buyer makes the offer, the price is* $p_{2B}^1 = \frac{(\pi(n)-\pi_0(n))}{2^{n-1}} + (\pi(n) - \pi_l(n))(1 - \frac{1}{2^{n-2}})$.

If the innovation is bad, it is not sold at a positive price.

[9] The assumption that a breakdown may occur before the first round will prove essential to limit the multiplicity of equilibria: see the Appendix.

It is clear that the license will be signed with the first buyer in the sequence. First, assumption 1 ($\pi(n)-\pi_0(n) > 0$) guarantees that there are gains from trade with the last buyer: should bargaining fail with all the previous buyers, it will succeed with the last buyer in the sequence. Second, the buyer positioned earlier in the sequence has even more incentive to sign, since he expects π_l rather than π_0 if he does not sign himself. He will thus pay a higher price for the license. Finally, we show recursively that each buyer has to leave a higher rent to the buyer than the next potential buyer. In equilibrium, the license is thus signed with the first buyer.

5.2.2 Bargaining in the first period

We denote by $p_2^g \equiv \frac{p_{2B}^1+p_{2S}^1}{2} = \frac{\pi-\pi_0}{2^n} + (\pi-\pi_l)(1-\frac{1}{2^{n-1}})$. This price is the expected payoff of a good type innovator before the first round of negotiations takes place in period 2. The expected payoff of a bad type innovator in the same situation is zero.

Proposition 11 *A license is sold in the first period to the first buyer in the sequence iff the following condition is satisfied:*

$$\Delta \geq \hat{\Delta}(n) \equiv p_2^g - q(\pi(n) - \pi_l(n)) \tag{7}$$

Again, the technology will be transferred early iff the development cost is sufficiently large, that is, above a threshold $\hat{\Delta}(n)$. When the profits do not depend on n, this threshold increases in n:[10] the condition for early licensing is harder to meet as the number of buyers increases. By contrast, when the profits depend on n, the effect of n on the efficiency threshold is ambiguous. If $\pi'(n) \leq \pi_l'(n)$, then for sufficiently large values of n, the efficiency threshold decreases with n.[11] We show for instance in the Appendix that for a standard Cournot model with cost-reducing innovation, the efficiency threshold has an inverted-U shape: it first increases, then decreases in n.

6 Empirical analysis

The results of our theoretical model are tested on data from the pharmaceutical industry. We do not attempt to establish a causal link between market structure and the timing of transfer, but rather to show that the link between these variables in the data is consistent with our model.

6.1 Background on the pharmaceutical industry

The pharmaceutical industry is very good illustration of the process we captured in our model. There appears to be an increasing division of labor between small biotechnology firms and large

[10] The sign of $\frac{\partial\hat{\Delta}}{\partial n}$ is that of $\pi + \pi_0 - 2\pi_l$, which is positive by assumption.
[11] Proof available upon request

pharmaceutical companies. In a 2006 survey of innovation, *The Economist* notes that "Big Pharma's R&D activity is now concentrated as much on identifying and doing deals with small, innovative firms as it is on trying to discover its own blockbuster drugs" (Economist (2006)). Biotechnology companies seem to have a comparative advantage in early stage discovery, while large pharmaceutical firms are considered more efficient in conducting later stage clinical testing. For example, they can exploit their relationships with medical practitioners who participate in running clinical trials or prescribe their other products. They also may benefit from economies of scale and scope in the administration of clinical trials. Drug candidates are usually sold with exclusive licensing contracts.[12]

In two variants of our model, the seller has different beliefs or better information about the value of the R%D project than the potential buyers. As discussed previously, the difference in their beliefs could be a result of asymmetric information or overconfidence. The empirical literature attempting to assess the extent of adverse selection in this industry obtains mixed results. Pisano (1997) finds higher failure rates of drug candidates licensed in from biotechnology firms than those developed in-house by pharmaceutical firms, suggesting a "lemons" problem, though Arora et al. (2004) find the opposite. However, there is at least casual evidence that industry practitioners worry about buying a lemon. We find it plausible that the licensing firm has some additional information about the value of its drug candidate, even if considerable uncertainty exists. In particular, it may know more about possible shortcomings: it may have internal information that suggests problems or limitations, but that cannot be credibly disclosed. As discussed in 4.2, Cockburn (2007) present survey evidence supporting this point.

The idea that entrepreneurs or innovators are overoptimistic has received more theoretical attention than empirical study. Lowe & Ziedonis (2006) found evidence consistent with entrepreneurial overconfidence in a study of university technology transfer; in particular, entrepreneurs in their sample were more likely to pursue failed development efforts than were more established firms. We are not aware of any work that focuses specifically on overconfidence in biotechnology firms when licensing. In a study of cancer drug candidates, Guedj & Scharfstein (2004) show that smaller biotech firms are more likely to advance their projects from Phase I to Phase II than larger or more experienced firms, but see higher failure rates later on. However, the authors interpret this pattern as evidence of an agency problem between managers and shareholders rather than overconfidence. In general, it is difficult to draw firm conclusions about each party's beliefs on the quality of a licensed drug from ex post performance. Higher failure rates alone do not establish asymmetric information or overconfidence, as both parties could agree that a project is high risk and agree on a license price that reflects that risk. Without access to internal documents that include assessments of risk, we cannot distinguish between information asymmetry and overconfidence. In our empirical analysis (see section 7.2), we examine the effect of market structure in cases where the severity of

[12]Even though direct acquisitions of the company also occur, we will focus in the empirical analysis on the licensing channel.

asymmetric information may differ. Unfortunately, we lack a similar proxy for overconfidence.

The last important element of the model is that verifiable information is revealed during the development process. Drug development involves several distinct phases which are clearly defined and controlled by regulatory agencies such as the FDA in the United States or the European Medicines Agency (EMA). During the discovery phase, firms identify drug candidates for further development in targeting a disease or indication. These are tested in animal subjects during the preclinical phase. At this point, clinical trials in humans begin. Phase I trials involve a small number of healthy volunteers to establish a drug candidate's safety. Phase II trials focus on the efficacy of the drug candidate in treating patients with the disease and begin to identify side effects. Phase III trials are much larger studies that continue to gather data on safety and efficacy. Verifiable evidence of a drug candidate's quality is produced at each phase and presented to the regulatory agencies.

As we noted earlier, a number of alternative assumptions yield the same predicted effect of market structure in our model.[13] While we think the revelation of information from clinical trials is of clear importance in this context, the existence of a different type of information asymmetry is also possible: buyers might have superior knowledge of the downstream market and profit potential. However, this type of asymmetry is unlikely to decrease as the product is developed, and so it is unlikely to affect the timing of licensing.

6.2 Data

We draw our sample of licensing contracts from Recombinant Capital's rDNA database. It contains detailed information on all licensing deals in the pharmaceutical industry signed since 1973, including financial details (total value, upfront and milestone payments, royalty rates) for a subset of the agreements. It also provides information about the geographical region covered by the license and about the type of contract (marketing, production, research). Finally, it records the phase of development of the drug at the time the license was signed.

We do not model the choice of vertical integration vs. licensing, only the timing of a license conditional on the signing of a contract. For small biotech firms, it is very rare to observe projects developed without assistance from another firm at some point. In other words, we take it as given that a small firm must license, and focus on when. If competition introduces sample selection by affecting the likelihood that any license is signed, then our estimated coefficients should be interpreted as applicable only to this subset.

Testing our theory requires us to identify a downstream market and the number of potential licensees of an innovation. Since the rDNA database contains no information on potential licensees or any other market level data, we exploit additional data sources called R&D Focus and MIDAS,

[13]For example, buyers may learn about the number of competing bidders for a project. We could not come up with a convincing empirical test of this assumption, however.

produced by IMS Health. MIDAS provides us with annual data on total revenues by disease from 15 countries from 1993-2007. The R&D Focus database tracks all drug candidates, or projects, in development since the early 1990s. This source allows us to create measures of each firm's experience in drug development as well as in marketing approved products at the disease level.

We used a number of standard sources for firm-level information, such as VentureXpert, Compustat, Osiris, and CorpTech. We identify whether each firm is publicly traded or privately held and collect some financial data, where possible, such as the amount of venture capital financing. Because many of the firms in our study are privately held and/or non US (roughly half are headquartered outside of the United States), our financial information is somewhat limited.

We restrict our analysis to contracts involving R&D on drug candidates that have not yet been approved for launch, excluding co-marketing alliances. We focus on exclusive deals with no geographic restriction, and on deals that are signed in the discovery, preclinical or clinical phases of development. In order to match each deal to market-level variables for which we have data, we include deals from 1990-2007. These exclusions reduce our sample of interest to 6,426 (including observations for which the stage at signing is missing) from a total of 14,976 deals in ReCap. In practice, this requires us to match each licensing agreement from the rDNA database with a project in the R&D Focus database by hand using information on the partnering firms and the subject of the license. In addition, we concentrate on deals that involve a specific drug candidate (or candidates, in some cases) rather than those for the use of a technology platform (which are rarely exclusive agreements). This process results in 2335 matches. We have the least success in matching very early stage deals and those where the stage at signing is missing in the rDNA database.

Important for our definitions of potential buyer and downstream market is a drug's Anatomical Therapeutic Chemical classification (hereafter therapeutic class).[14] Therapeutic classes correspond to disease markets, and are coded at different levels of specificity. For example, the broadest level is a single letter, such as group C for cardiovascular system therapies. C02 refers to the subgroup of antihypertensive therapies, and C02A is the narrower set of centrally-acting antiadrenergic agents. Drugs within a therapeutic class may be considered substitutes, but drugs within the same narrow class are closer substitutes than those in the same broad class. Substitution is unlikely across therapeutic classes. For example, "acne" (D10) is a separate market from "diabetes" (A10), and human insulins (A10A) are closer substitutes than oral antidiabetics (A10B) in the treatment of diabetes. We exclude the therapeutic class V7 (defined as "All other non-therapeutic products") because the set of products assigned to this class are not substitutes for each other.

[14]The World Health Organization describes this classification scheme as follows: "In the Anatomical Therapeutic Chemical (ATC) classification system, the drugs are divided into different groups according to the organ or system on which they act and their chemical, pharmacological and therapeutic properties. Drugs are classified in groups at five different levels. The drugs are divided into fourteen main groups (1st level), with one pharmacological/therapeutic subgroup (2nd level). The 3rd and 4th levels are chemical/pharmacological/therapeutic subgroups and the 5th level is the chemical substance. The 2nd, 3rd and 4th levels are often used to identify pharmacological subgroups when that is considered more appropriate than therapeutic or chemical subgroups."

Drug candidates are often assigned to multiple therapeutic classes because they can treat different diseases. In addition, most drug candidates have more than one firm listed as co-developers. When counting the number of firms active in a therapeutic class, we consider all firms that are involved in the development of a project, and we include all projects that are assigned to the therapeutic class. Thus, our measures of the number of firms in a therapeutic class are very inclusive.

Table 1 provides summary statistics for the key variables in our analysis. We examine only drug candidates that were licensed between 1990 and 2007, not the set of all drug candidates that were ever (or are currently) available for licensing. Our estimates therefore apply only to a selected sample. All variables are measured as of the date a license was signed. The definitions of incumbents and entrants are described in section 7.3.

6.3 Empirical specification

While potential buyers vary in size, existing portfolios of products, and many other factors, the empirical approach we adopt does not allow for buyer characteristics to enter except through our definition of the set of potential buyers or classification as entrant/incumbent, which we discuss below. Our focus is not on the identity of the buyer, but rather on the timing of the sale.

We begin by testing the model of section 3.2.3, which differentiates incumbents with stakes on the markets and potential entrants. We use three empirical methods: logit, ordered logit and a hazard rate model. The first approach defines an "early" stage of licensing (the discovery and preclinical phases) and a "late" stage (Phase I, II and III trials). Testing involving human subjects is more expensive and requires more complicated study design, and it is during these phases of development that large, experienced firms probably have a comparative advantage. An alternative is to treat each of these distinct phases as a "period" and assume that a similar trade-off exists between signing in stage i and delaying until stage $i+1$ for each stage i; the difference is that rather than disappearing completely, the informational asymmetry shrinks as each development stage is completed. We can think of the condition for signing a license described in Proposition 1 as an unobserved latent variable y^*. Two natural empirical models are the logit (for early vs. late) and ordered logit (for each phase of development). Our latent regression is

$$y^* = \beta N + \gamma X + \epsilon$$

where N is a vector of competition measures and X is a vector of controls, described below.

The logit and ordered logit approaches have a number of appealing features. They correspond very closely to our theoretical model, where the two periods differ in the information available to the potential buyers. As a drug candidate progresses through each stage, verifiable information about its quality is indeed revealed. This revelation exposes the innovator's overconfidence, or reduces the degree of asymmetric information. Another approach, similar to that taken by Gans et al. (2008), is a hazard model in which a biotechnology firm's innovation is "at risk" for licensing

Table 1: Summary statistics

Variable	N	Mean	StdDev	Min	Max
Late signing (post-preclinical)	2066	0.29	0.45	0.0	1.0
Log(months since start of preclinical)	1814	1.12	1.82	0.0	5.6
Licensor market experience (no. drugs marketed)	2047	3.20	13.65	0.0	198.0
Licensor development experience (no. drugs in development)	2047	6.38	16.44	0.0	302.0
Licensor deal experience (no. deals previously signed)	2047	1.49	2.47	0.0	17.0
Licensor is publicly traded	2066	0.15	0.36	0.0	1.0
Licensor is based outside US	2066	0.42	0.49	0.0	1.0
Firms are co-located (same country of headquarters)	2066	0.42	0.49	0.0	1.0
Licensor is not in VentureXpert data	2047	0.49	0.50	0.0	1.0
Licensor's round of venture financing	1026	3.69	2.68	1.0	20.0
Licensor's funding in last round of venture financing	1026	10.90	18.65	0.0	150.0
Licensor's cumulative venture financing	1026	28.52	33.11	0.0	244.6
Licensor's age	1048	8.23	5.60	0.0	20.0
Total revenues in therapeutic class (millions of US$)	1672	4.27	4.77	0.0	30.6
Total venture funding for industry (units of US$)	2065	9.15	4.23	0.0	16.7
Potential buyers	2047	42.40	27.73	0.0	113.0
Incumbents that sign at least one license	2047	22.78	19.95	0.0	80.0
Entrants that sign at least one license	2047	19.62	15.06	0.0	94.0
Incumbents, all firm types	2047	63.51	59.09	0.0	243.0
Entrants, all firm types	2047	35.92	33.87	0.0	230.0
Incumbents that are large and public	2047	8.13	5.09	0.0	20.0
Entrants that are large and public	2047	7.67	5.35	0.0	24.0

from the time the drug candidate reaches the preclinical stage of development, and examine what factors affect the hazard rate of the drug candidate's transfer to a licensee. Since censoring is not an issue in our data, we take the simplest approach and regress the natural log of the months since a drug candidate entered the preclinical phase on the same variables as used in the ordered logit. There is considerable heterogeneity in the time required to complete clinical trials; drugs for chronic conditions may require longer trials than those for acute conditions, for example, and a hazard model may confound the complexity of trials with the strategic delay that is our interest.

We exploit variation in the number of competitors across therapeutic classes, and within therapeutic classes at different points in time, to identify the effect of market structure. Naturally, any regression in which competition appears as an explanatory variable raises concerns about endogeneity. The regression model is derived from an equilibrium condition that accounts for the effect of competition on profits. Given the entry barriers and lengthy development times required, the number of competitors in a market is largely fixed in the short run; new entry reflects business decisions taken years before, rather than an endogenous response to early or late-stage licensing. The number of competitors also changes if a merger takes place, but it seems unlikely that mergers between large firms are motivated by the timing of license contracts. Our main concern is the existence of an omitted variable that is correlated with differences in competition between therapeutic classes and with the timing of licensing, which is testable only with a potential instrument for competition. While it is not clear what such an omitted variable might be (additional controls are discussed below), we lack good candidates to instrument for the number of competitors. No major regulatory change affecting competition occurred during our sample period, and we have no geographic variation in competition. Therefore, we interpret our results with caution.

While the the relationship between timing and competition is our main focus, we include a number of controls that our model (and the existing literature) suggest should affect licensing behavior. These include the extent to which a licensor faces capital constraints and various other factors such as experience in licensing (measured as the number of previous licenses the biotech firm has granted), experience in drug development (measured as the number of drug candidates the licensing firm has previously initiated), market experience (measured as the number of drugs the licensing firm has successfully launched). Because the availability of financing may vary over time, we also include annual commitments by venture capitalists within the biotechnology and medical industries. All specifications also include therapeutic class fixed effects, to control for differences in demand as well as development costs or risks that are likely to vary by disease, and a control for the size of the therapeutic class market, measured as total annual revenues from 15 countries for drugs assigned to that therapeutic class. Standard errors are clustered by disease in all models reported here.

7 Results

The main challenge we face for our empirical exercise is to define a potential buyer. We argue that firms with product market experience in the same disease area as the drug candidate for license are the most likely buyers. Such firms have a good understanding of the market potential and able to evaluate the scientific validity of a drug candidate available for license. In addition, these firms have pre-existing relationships with doctors who treat the disease, who may enroll patients in clinical trials as well as prescribe the drug once it is approved. In other words, these firms should have relatively lower costs of conducting clinical trials and marketing the product, and the highest expected profits from signing a license. We restrict the set of potential licensees of a drug candidate to firms with existing products in the same broad disease area, or 2-digit ATC, as the drug candidate licensed. For our baseline results, we focus on those firms that buy at least one license; this essentially means that we don't consider firms that mostly sell drug candidates (usually small biotechs) as potential buyers of other drug candidates. Any definition of potential licensee risks excluding some actual buyers and/or including some that are not true competitors for the license. We therefore repeat the analysis using different definitions of potential buyers, and these results are presented in section 7.3.

7.1 Entrants and incumbents

Potential buyers of a license may not be equally exposed to downstream competition and its countervailing effect on licensing delay. Firms that market a product in the same narrow disease area are most affected by downstream competition, while those that are active in related diseases are less so. We refer to the former as incumbents in the market, and the latter as potential entrants. We estimate the model of section 3.2.3 that differentiates between incumbents and entrants, in which we showed that the number of entrants unambiguously delays licensing. While the effect of the number of incumbents is ambiguous, we showed that in general we should expect an increase in the number of incumbents to reduce delays in licensing. We therefore use the number of entrants and incumbents as the main explanatory variables in the following specifications. We expect a negative coefficient on the number of incumbents and a positive coefficient on the number of entrants.

We define incumbents as firms with drugs in the same 3-digit ATC as the licensed drug, while entrants are firms with drugs in the same 2-digit ATC as the licensed drug, but not in the same 3-digit ATC. Both definitions include only firms that buy at least one license in our data. The results are presented in table 2; the specifications include all the additional explanatory variables as in our baseline case, but we report only the coefficients for incumbents and entrants. Across all specifications, the predictions of our theoretical model are confirmed: an increase in the number of incumbents (resp. entrants) decreases (resp. increases) licensing delays. To assess the importance of the effect of competition, we calculate the average elasticity of the probability of late signing

with respect to incumbents and entrants. The percentage change in the probability of late signing for a one-percent change in the number of incumbents is -0.31, and the corresponding figure for entrants is 0.17.

7.2 Overconfidence and asymmetric information

In our model, the presence of asymmetric information or overconfidence are sources of inefficient delay. While we cannot test for these directly or distinguish between them empirically, we try to establish their relevance by testing our model on different sub-samples for which we expect information asymmetries or the the innovator's overconfidence to be high or low. Asymmetric information and overconfidence are difficult to quantify, but we argue that they are likely to be greatest in the case of licensors that have yet to establish themselves as capable of producing good drug candidates or as trustworthy partners. Nicholson et al. (2005) show that these firms receive the largest discount from new partners, for example, and cite deal experience as a means of signalling quality. We therefore define "high asymmetry" licensors as those with fewer than 3 deals prior to its current one; we obtain similar results using a definition based on development experience. An alternative definition is based on a firm's status as a public or private firm. Public firms are subject to greater scrutiny and required by law to disclose specific information to shareholders. Therefore, we might expect public licensors to have less private information as well as less subject to liquidity constraints. We estimate our models using this split as well.

Table 3 indicates that our results are strongest for the subset of deals where asymmetric information or overconfidence is likely to be high (we report only a subset of coefficients but include the same set control variables as in the previous sets). Licensing agreements involving licensors with an established history of partnerships do not yield statistically significant coefficients on competition. Similarly, competition has a very small, although significant, effect on licensing agreements involving publicly traded licensors. We interpret these findings as additional support for our model: if the effect of competition were the same in both high asymmetry and low asymmetry cases, this would suggest that informational asymmetry and/or overconfidence are not underlying mechanisms driving the timing of licensing.

7.3 Alternative definitions of potential buyers

An important concern in the empirical analysis is that our key variables of interest, those for buyer competition, may be measured with error because we can't observe for certain which firms may have considered a license for a particular drug candidate. In this section, we explore alternative definitions of potential buyers. Our previous definition was based on the argument that firms with market experience in related areas would have the highest valuation for, and best ability to evaluate, potential drug candidates. In her paper on licensing of biotechnology drugs, Levine (2007) defines a potential buyer as any firm that markets a biotechnology product in the US, and allows their

Table 2: Results with incumbents and entrants

Variable	Logit	O-logit	Hazard
Intercept	-1.9810**	-1.4105**	0.1789
	(0.5126)	(0.4255)	(0.4054)
Incumbents	-0.0169**	-0.0232**	-0.0116**
	(0.0050)	(0.0042)	(0.0042)
Entrants	0.0113**	0.0080**	0.0145**
	(0.0041)	(0.0034)	(0.0035)
Total venture funding for industry	0.0194	0.0395**	0.0431**
	(0.0218)	(0.0183)	(0.0183)
Total revenues in therapeutic class	0.0572**	0.0554**	0.0320**
	(0.0147)	(0.0127)	(0.0129)
Licensor market experience	0.0063	-0.0029	0.0114
	(0.0108)	(0.0096)	(0.0096)
Licensor development experience	-0.0037	0.0071	-0.0118
	(0.0107)	(0.0095)	(0.0095)
Licensor deal experience	-0.0141	-0.0419**	-0.0029
	(0.0236)	(0.0204)	(0.0203)
Licensor is publicly traded	0.5598**	0.4871**	0.6930**
	(0.1785)	(0.1538)	(0.1549)
Licensor is based outside US	0.0774	0.1635	0.0160
	(0.1294)	(0.1092)	(0.1089)
Firms are co-located	-0.5788**	-0.4475**	-0.4403**
	(0.1289)	(0.1070)	(0.1045)
Licensor is not in VentureXpert data	0.4510**	0.5050**	0.4134**
	(0.2077)	(0.1733)	(0.1665)
Licensor's cumulative venture financing	0.0042	0.0050*	-0.0025
	(0.0035)	(0.0030)	(0.0031)
Licensor's funding in last round of venture financing	-0.0095	-0.0102**	0.0045
	(0.0060)	(0.0051)	(0.0049)
Licensor's round of venture financing	-0.0153	-0.0077	0.0387
	(0.0385)	(0.0332)	(0.0325)
Licensor's age	0.0697**	0.0710**	0.0785**
	(0.0157)	(0.0134)	(0.0138)
Number Obs	1633	1633	1449
Log L or R^2	-926.4657	-2069.873	.095

Table 3: Results comparing overconfidence/information asymmetry

Variable	High asym.	Low asym.	Private	Public
Incumbents	-0.0245**	-0.0031	-0.0202**	0.0048**
	(0.0059)	(0.0112)	(0.0056)	(0.0000)
Entrants	0.0086*	0.0180*	0.0116**	0.0103**
	(0.0045)	(0.0109)	(0.0000)	(0.0000)
Number Obs	1254	379	1388	245
Log L	-697.9432	-200.6718	-760.5830	-144.2832

valuation to depend on their experience in different disease areas. We consider non-US markets and do not distinguish prior marketing of a biotechnology product from that of small molecule drugs, but our previous definition also restricted the set of potential buyers to those that actually buy a license at least once in our data. In this section, we consider two alternative definitions of potential buyers to check the robustness of our findings.

First, we define incumbents and entrants as before except without the restriction that firms that buy a license at least once in our data set. This set includes many firms that may not be seeking to license in external drug candidates. For example, a small firm that co-developed a drug with a much larger partner, but that has no marketing capabilities of its own, is counted as a potential buyer under this definition. Table 4 presents the results from our three econometric models using this alternative definition. We again find a negative and significant coefficient on the number of incumbents and a positive and significant coefficient on the number of entrants. Second, we define incumbents and entrants as in the previous section except that we restrict buyers to be large, publicly traded firms (those we believe are most likely to have the necessary commercialization and marketing skills). The results, presented in table 5, are weaker in terms of statistical significance, though of the expected signs. Because most big firms are active in a large set of disease areas, there is less variance in the number of potential buyers across therapeutic classes for us to identify the effect of competition. As before, both tables report only the coefficients relevant to market structure, but all specifications include the same control variables as the baseline case.

8 Conclusion

We analyze the effect of competition on the efficiency of markets for R&D projects. While normally we expect competition to increase efficiency, one of the important conclusions from our model is that competition has two countervailing effects on the efficiency of markets for projects. A decrease in the number of incumbents or an increase in the number of entrants on the market may inefficiently delay the licensing of an project.

Table 4: Results with first alternative definition of potential buyers

Variable	Logit	O-logit	Hazard
Incumbents	-0.0035**	-0.0058**	-0.0025*
	(0.0016)	(0.0013)	(0.0013)
Entrants	0.0058**	0.0045**	0.0068**
	(0.0017)	(0.0014)	(0.0015)
Number Obs	1633	1633	1449
Log L or R^2	-927.4660	-2072.446	.095

Table 5: Results with second alternative definition of potential buyers

Variable	Logit	O-logit	Hazard
Incumbents	-0.0254	-0.0496**	-0.0031
	(0.0211)	(0.0177)	(0.0175)
Entrants	0.0232*	0.0106	0.0337**
	(0.0127)	(0.0104)	(0.0105)
Number Obs	1633	1633	1449
Log L or R^2	-932.5247	-2081.531	.087

We present a model of auction that incorporates a number of elements that characterize markets for projects in practice. Of particular importance is the uncertainty about the value of the innovation that disappears with time. The seller is more confident than the buyers about the potential value of the project. We are able to obtain testable predictions that are confirmed by our empirical analysis. Our empirical results on the effect of competition on licensing delays are economically significant.

The theoretical finding that competition has countervailing effects on delays in licensing appears to be robust: we obtain similar results with a bargaining model and with an auction model. Though the pharmaceutical industry is particularly well-suited for our application, our results should be relevant in any industry where the division of labor in the innovative process exists, where early stage innovators have better information on the quality of their innovation than later developers, and where innovators face a higher cost of providing information about quality through the development process than do potential buyers. One example of such an environment is university technology transfer. Projects generated by faculty may be difficult to transfer because academic scientists face a very high cost of proving their quality. They may lack the necessary equipment or staff to produce verifiable information, in addition to having an orientation towards basic research.

Our model is not specifically designed to analyze the issue of mergers, but our results suggest that merger reviews in highly technological areas should consider this additional effect of the merger

on upstream licensing markets. The pharmaceutical industry has undergone significant consolidation in recent decades, particularly between the large multinationals that are the typical buyers of licenses. In addition, there is much concern regarding a slowdown of innovation in this industry that the widespread use of licensing has failed to reverse. This paper highlights some frictions in licensing and the role of competition that may at least partially explain these patterns.

References

Allain, M.-L., Henry, E., & Kyle, M. (2011). Inefficiencies in Technology Transfer: Theory and Empirics. Tech. Rep. 8206, CEPR.

Anand, B., & Khanna, T. (2000). The Structure of Licensing Contracts. *Journal of Industrial Economics*, *48*(1), 103–135.

Angell, M. (2004). *The Truth About the Drug Companies: How They Deceive Us and What to Do About It*. Random House.

Anton, J., & Yao, D. (2002). The Sale of Ideas: Strategic Disclosure, Property Rights and Contracting. *The Review of Economic Studies*, *69*, 513–531.

Arora, A., Fosfuri, A., & Gambardella, A. (2001). *Markets for Technology: The Economics of Innovation and Corporate Strategy*. MIT Press.

Arora, A., & Gambardella, A. (2010). Ideas for Rent: An Overview of Markets for Technology. *Industrial and Corporate Change*, *19*(3), 775–803.

Arora, A., Pammolli, F., Vogt, W. B., & Yoon, J. (2004). Does in-house R&D increase bargaining power? Evidence from the Pharmaceutical Industry. Carnegie Mellon University Working Paper.

Arrow, K. (1971). *Essays in the Theory of Risk-Bearing*. North-Holland Publishing Company.

Beggs, A. (1992). The Licensing of Patents Under Asymmetric Information. *International Journal of Industrial Organization*, *10*, 171–191.

Choi, J. (2001). Technology Transfer with Moral Hazard. *International Journal of Industrial Organization*, *19*(249-266).

Cockburn, I. (2007). Is the Market for Technology Working Well? Obstacles to Licensing and Ways to Overcome Them. Conference Paper, Conference on Economics of Technology Policy.

Danzon, P. M., Nicholson, S., & Pereira, N. (2005). Productivity in Pharmaceutical-Biotechnology R&D: The Role of Experience and Alliances. *Journal of Health Economics*, *24*(2), 317–339.

Economist (2006). The tortoise and the hare: the search for innovation. *The Economist*, *January 19*.

Galasso, A., & Simcoe, T. (2011). CEO Overconfidence and Innovation. *Management Science*, *57*, 1469–1484.

Gans, J. S., Hsu, D. H., & Stern, S. (2008). The Impact of Uncertain Intellectual Property Rights on the Market for Ideas: Evidence from Patent Grant Delays. *Management Science*, *54*, 982–997.

Guedj, I., & Scharfstein, D. (2004). Organizational Scope and Investment: Evidence from the Drug Development Strategies and Performance of Biopharmaceutical Firms. NBER Working Paper 10933.

Hayward, M., Shepherd, D., & Griffin, D. (2006). A Hubris Theory of Entrepreneurship. *Management Science*, *52*(2), 160–172.

Hegde, D. (2013). Tacit Knowledge and the Structure of License Contracts: Evidence from the Biomedical Industry. *Journal of Economics and Management Strategy*, *forthcoming*.

Higgins, M. J. (2007). The allocation of control rights in pharmaceutical alliances. *Journal of Corporate Finance*, *13*, 58–75.

Kamien, M., & Tauman, Y. (1986). Fees vs. Royalties and the Private Value of a Patent. *Quarterly Journal of Economics*, *101*(3), 471–491.

Lerner, J., & Malmendier, U. (2005). Contractibility and the Design of Research Agreements. NBER Working Paper 11292.

Lerner, J., & Merges, R. P. (1998). The Control of Technology Alliances: An Empirical Analysis of the Biotechnology Industry. *Journal of Industrial Economics*, *XLVI*(2), 125–156.

Levine, A. (2007). Licensing and Scale Economies in the Biotechnology Pharmaceutical Industry. Working paper, Stanford University.

Lowe, R. A., & Ziedonis, A. A. (2006). Overoptimism and the Performance of Entrepreneurial Firms. *Management Science*, *52*(2), 173–186.

Luo, H. (2011). When to Sell Your Idea: Theory and Evidence from the Movie Industry. Harvard Business School Working Paper, No. 12-039.

Malmendier, U., & Tate, G. (2005). CEO Overconfidence and Corporate Investment. *Journal of Finance*, *60*(6), 2661–2770.

Mendi, P. (2005). The Structure of Payments in Technology Transfer Contracts: Evidence from Spain. *Journal of Economics and Management Strategy*, *14*(2), 403–429.

Motta, M. (2004). *Competition Policy. Theory and Practice*. Cambridge, UK: Cambridge University Press.

Nicholson, S., Danzon, P. M., & McCullough, J. (2005). Biotech-Pharmaceutical Alliances as a Signal of Asset and Firm Quality. *Journal of Business*, *78*(4), 1433–1464.

Pisano, G. (1997). R&D Performance, Collaborative Arrangements and the Market for Know-How: A Test of the Lemons Hypothesis in Biotechnology. Available at SSRN: http://ssrn.com/abstract=41980.

Shubik, M., & Levithan, R. (1980). *Market Structure and Behavior*. Cambridge, MA: Harvard University Press.

Vishwasrao, S. (2006). Royalties vs. Fees: How do Firms Pay for Foreign Technology. *International Journal of Industrial Organization*, *25*, 741–759.

Wuyts, S., & Dutta, S. (2008). Licensing Exchange: Insights from the Biopharmaceutical Industry. *Internation Journal of Research in Marketing*, *25*(4), 273–281.

Ziedonis, A. (2007). Real Options in Technology Licensing. *Management Science*, *53*(10), 1618–1633.

9 Appendix

9.1 Lemma 1

Second period: In the second period, the value of the innovation is known. If the innovation is good, an auction is run. The unique equilibrium is such that all buyers bid exactly their valuation (equilibrium bidding strategy in a second price auction). Thus in the second period, bidder i bids $\pi(n) - \pi_l(n) - c_i$.

The profit of the seller is:

$$p_2(n) = \pi(n) - \pi_l(n) - c_{n2} \tag{8}$$

and the profit of the buyer (with cost c) from winning the auction is:

$$c_{n2} - c + \pi_l(n) \tag{9}$$

where c_{n2} is the second lowest cost among n draws of the cost parameter.

First period: we show that it is a dominant strategy for buyer i with cost c_i to bid $b_i = q(\pi(n) - \pi_l(n) - c_i)$.

Case 1 bid b_i is the highest bid. In that case bidding more does not affect the payoff. Bidding less can make you lose and yield payoff $q\pi_l(n)$. Bidding b_i yields payoff: $q(\pi(n) - c_i) - b_{n2}$ (where b_{n2} is the second highest bid). Since $q(\pi(n) - c_i - \pi_l(n)) > b_i > b_{n2}$, this deviation decreases the bidder's payoff.

Case 1 bid b_i is not the highest bid. Denote the highest bid b_1 in that case. Bidding less than b_1 doesn't change the outcome. Bidding more yields payoff $q(\pi(n) - c_i) - b_1$. This is an optimal deviation if $b_1 < q(\pi(n) - c_i - \pi_l(n))$. By definition of $b_i = q(\pi(n) - c_i - \pi_l(n))$, since $b_i < b_1$ this cannot be an optimal deviation.

Proposition 2: the efficiency threshold is given by:

$$\underline{\Delta}(n) = (p - q)\left(\pi - \pi_l - E[c_{n2}]\right). \tag{10}$$

As $E[c_{n2}]$ is decreasing in n (the higher the number of draws, the lower the expected second lowest cost), we have $\underline{\Delta}'(n) > 0$.

Proposition 3

$\underline{\Delta}(n)$ decreases in n if $\pi(n) - \pi_l(n)$ decreases more than $E[c_{n2}]$. We have

$$F_{2n}(X) \equiv P(c_{n2} \leq X) = \sum_{k=2}^{n} C_n^k F(X)^k (1 - F(X))^{n-k}$$

Hence the general formula of the $2nd$ order statistics of the distribution of c on $[\underline{c}, \overline{c}]$:

$$E[c_{n2}] = \overline{c} - \sum_{k=2}^{n} C_n^k \int_{\underline{c}}^{\overline{c}} F(X)^k (1 - F(X))^{n-k} dX$$

If we assume a uniform distribution of c on $[0, \overline{c}]$ then c_{n2} follows a $Beta(2, n-1)$ distribution; then $E[c_{n2}] = \frac{2\overline{c}}{n+1}$. Then $\underline{\Delta}(n)$ decreases in n iff $\pi'(n) - \pi'_l(n) < \frac{-2c}{(n+1)^2}$.

The following example illustrates this case in a simple framework. Assume that n buyers initially sell n symmetrically differentiated goods with a constant marginal cost $c \in [0, 1]$. They compete in prices. Following Motta (2004), we derive a simple model of consumer preferences from Shubik & Levithan (1980): the consumer's utility is given by

$$U(q_1, ..., q_n) = \sum_{i=1}^{n} q_i - \frac{n}{2(1+\mu)} \left[\sum_{i=1}^{n} q_i^2 + \frac{\mu}{n} (\sum_{i=1}^{n} q_i)^2 \right]$$

where q_i is the quantity of good i consumed and μ is the degree of product substitution between the goods ($\mu \in [0, +\infty]$). The demand for each good is thus:

$$D_i = \frac{1}{n} \left(1 - p_i(1+\mu) + \frac{\mu}{n} \sum_{j=1}^{n} p_j \right).$$

The innovation allows the introduction of a new product. If no license is signed, the market is composed of n symmetric firms with differentiated products. If one firm, say n, signs a license with the (good) innovator, it introduces a new product. The competition game is now asymmetric, with the licensee selling two of the existing $(n+1)$ products.

The equilibrium of the pricing game yields the following profits:

$$\begin{aligned} \pi &= \Pi_n = \frac{(c-1)^2(1+n+\mu(n-1))(2+\mu+2n(1+\mu))^2}{2(1+n)^2(2-\mu^2+n(\bar{1}+\mu)(2+\mu))^2} \\ \pi_l &= \Pi_i = \frac{(c-1)^2(1+n+\mu n)^3}{(1+n)^2(2-\mu^2+n(\bar{1}+\mu)(2+\mu))^2} \text{for } i \in \{1, ..., n-1\} \end{aligned}$$

Whenever $\overline{c}$ is such that developing the innovation is profitable for the buyer with the highest cost (that is, $\pi - \pi_l - \overline{c} > 0$), tedious but simple computation shows that the efficiency threshold $\underline{\Delta}$ decreases in n for all $\mu > 0, n > 2$ and $c \in [0, 1]$.[15]

Proposition 4: entrants and incumbents

Assume that, if the innovation is good, an entrant receives a profit $\pi_e(n+1)$ if he buys the license, while he receives a zero profit if he fails to buy it (irrespective of who buys it: he simply

[15] Computations available upon request.

stays out of the market if he does not buy the license). An incumbent is assumed to receive $\pi(n)$ if he buys the license, $\pi_l(n+1)$ if an entrant buys the license, and $\pi_l(n)$ if another incumbent buys the license.

We consider in turn the four possible cases:

- If $(\pi(n) - \pi_l(n) - c_{n1} \geq)\pi(n) - \pi_l(n) - c_{n2} \geq \pi_e(n+1) - c_{e1}$, the two highest bidders (in each period) are incumbents. In the second period, if the innovator runs an auction, each entrant j bids $\pi_e(n+1) - c_j$, while each incumbent bids $\pi(n) - \pi_l(n) - c_i$. Consider the first period. If the innovator does not set up an auction, her expected gain is $p(\pi(n) - \pi_l(n) - c_{n2}) - \Delta$. If she sets up an auction in the first period, each entrant j bids $q[\pi_e(n+1) - c_j]$, while each incumbent bids $q[\pi(n) - \pi_l(n) - c_i]$, and an incumbent wins the auction. The expected gain for the seller is then $q(\pi(n) - \pi_l(n) - c_{n2})$.

  the condition for the innovator to run an auction in period 1 is then

  $$\Delta \geq (p-q)(\pi(n) - \pi_l(n) - E[c_{n2}]),$$

  which in independent on e.

- If $\pi(n) - \pi_l(n) - c_{n1} \geq \pi_e(n+1) - c_{e1} \geq \pi(n) - \pi_l(n) - c_{n2}$, in each period, the highest bidder is an incumbent while the second-highest is an entrant; the condition for the innovator to run an auction in period 1 is then

  $$\Delta \geq (p-q)(\pi_e(n+1) - E[c_{e1}]),$$

  which increases in e;

- If $\pi_e(n+1) - c_{e1} \geq \pi(n) - \pi_l(n) - c_{n1} \geq \pi_e(n+1) - c_{e2}$, then

  - either $\pi_e(n+1) - c_{e1} \leq \pi(n) - \pi_l(n+1) - c_{n1}$, and, in any auction, an incumbent wins and pays the second-highest bid $\pi_e(n+1) - c_{e1}$. The condition for the innovator to run an auction in period 1 is then

    $$\Delta \geq (p-q)(\pi_e(n+1) - E[c_{e1}]),$$

    which increases in e;

  - or $\pi_e(n+1) - c_{e1} \geq \pi(n) - \pi_l(n+1) - c_{n1}$, and, in any auction, an entrant wins and pays the second-highest bid $\pi(n) - \pi_l(n+1) - c_{n1}$. The condition for the innovator to run an auction in period 1 is then

    $$\Delta \geq (p-q)(\pi(n) - \pi_l(n+1) - c_{n1}),$$

which is independent on e.

- If, finally, $\pi_e(n+1) - c_{e1} \geq \pi_e(n+1) - c_{e2} \geq \pi(n) - \pi_l(n) - c_{n1}$, in each period an entrant wins the auction. Then
  - either $\pi_e(n+1) - c_{e2} \leq \pi(n) - \pi_l(n+1) - c_{n1}$, and the second highest bidder is an incumbent. The condition for the innovator to run an auction in period 1 is then

$$\Delta \geq (p-q)(\pi(n) - \pi_l(n+1) - c_{n1}),$$

    which is independent on e;
  - or $\pi_e(n+1) - c_{e2} \geq \pi(n) - \pi_l(n+1) - c_{n1}$, and, in any auction, the second highest bidder is an entrant. The condition for the innovator to run an auction in period 1 is then

$$\Delta \geq (p-q)(\pi_e(n+1) - c_{e2}),$$

    which increases in e.

The following condition guarantees that an entrant wins the auction, and that the second-highest bid is always from an entrant:

$$\pi_e(n+1) - \overline{c} \geq \pi(n) - \pi_l(n+1),$$

under this condition, in both periods the price paid to the innovator is $\pi_e(n+1) - c_{e2}$. The seller thus sets up an auction in the first period iff:

$$\Delta \geq \underline{\Delta_e}(n) \equiv (p-q)(\pi_e(n+1) - E[c_{e2}]),$$

where $E[c_{e2}]$ is the expected value of the second-lower cost among e draws of the cost parameter.

$\underline{\Delta_e}(n)$ increases in e as $E[c_{e2}]$ decreases in e, while $\underline{\Delta_e}$ decreases in n as $\pi_e(n+1)$ decreases in n.

Proposition 5

Assume that condition 5 is satisfied: if the innovator develops the product herself, she exerts high effort, but if a buyer develops the product, he exerts a low effort.

First, if an auction is run in period 2, each buyer i knows that the innovation is good and then bids $\pi_H - \pi_l - c_i$. If an auction is run in period 1, with a milestone payment, buyer i is ready to pay the following tariff: $\pi_L - \pi_l - c_i$ if the innovation is good and 0 if it is bad.

Consider now the innovator's choice in period 1. She can either wait until period 2, which brings up an expected profit of $p(\pi_H - \pi_l - E[c_{n2}]) - \Delta_H$, or run an auction now, which brings up an expected payment of $p(\pi_L - \pi_l - E[c_{n2}])$.

The innovator thus waits for period 2 to run an auction if and only if:

$$p\pi_H - \Delta_H \geq p\pi_L,$$

which is satisfied under condition 5.

Proposition 6

In the second period, the type of the inventor is known, and the solution is the same as in Proposition 1.

First period

We show that the unique equilibrium is such that a player with cost c bids his expected valuation $q[\pi - \pi_l - c]$.

We first note that, for a buyer with cost c, bids strictly above $q[\pi - \pi_l - c]$ are dominated by bids equal to zero. We eliminate such strategies. After elimination of these strategies, we show that bidding exactly $q[\pi - \pi_l - c]$ is a dominant strategy for a player with cost c. Consider a bid $b < q[\pi - \pi_l - c]$. There are three cases to be considered:

Case 1 bid b is the highest bid. In that case bidding $q[\pi - \pi_l - c]$ does not change the outcome (outcome purely determined by the second highest bid).

Case 2 bid b is not the highest bid. We denote b_1 the highest bid in that case. If $b_1 > q[\pi - \pi_l - c]$ deviating to bidding $q[\pi - \pi_l - c]$ has no effect. If $b_1 \leq q[\pi - \pi_l - c]$, the expected profits if a bid $q[\pi - \pi_l - c]$ is made is $q[\pi - \pi_l - c] - b_1 \geq 0$. Thus bidding $q[\pi - \pi_l - c]$ is preferable to bidding b that gives zero profits.

In the first period the innovator has to decide whether or not to run an auction. Her expected profit in an auction is $q[\pi - \pi_l - E[c_{n2}]]$. If she decides to wait for the second period to conduct the auction, she expects profits $\pi - \pi_l - E[c_{n2}] - \Delta$ if she is a good type, and zero otherwise. Thus a good innovator runs an auction in the first period if and only if

$$\Delta \geq (1 - q)(\pi - \pi_l - E[c_{n2}])$$

As Δ is known by all potential buyers, running an auction in the first period if this condition is not satisfied signals a bad type innovator, and no buyer bids a positive price: such a deviation is therefore not profitable.

Proposition 8

In period 2, the buyers observe the actual number n of buyers. If an auction is run in period 2, and if $n \geq 2$, each of them thus bids $\pi(n) - \pi_l(n) - c_i$: the expected gain for the seller from running an auction in period 2 is $\pi(n) - \pi_l(n) - E[c_{n2}] - \Delta$. By contrast, if $n = 1$, the buyer bids 0 in period 2 and the expected gain for the seller of running an auction in period 2 is $-\Delta$.

We claim that, if $\Delta \leq \pi(n) - \pi_l(n) - E[c_{n2}]$, there exists a separating equilibrium where:

- The seller runs an auction in period 2 if $n \geq 2$;
- The seller runs an auction in period 1 if $n = 1$.
- If an auction is run in period 1, all buyers bid 0;
- If an auction is run in period 2, each buyer bids $\pi(n) - \pi_l(n) - c_i$.

Assume that the seller follows the above strategy. Then if a buyer observes that an auction is run in period 1, he believes he is the only possible buyer, and thus bids 0. All buyers do the same and the license is sold at a zero price: the seller gains 0. If by contrast no auction is run in period 1, in period 2 the real number of buyers is observed by all and the seller gains $\pi(n) - \pi_l(n) - E[c_{n2}] - \Delta > 0$.

Consider a deviation by the seller, who runs an auction in period 1 although $n \geq 2$. Given the beliefs and strategy of the buyers', the deviation yields a zero profit instead of a positive profit: it is not profitable. Similarly, given the seller's strategy, no deviation by a buyer is profitable. QED.

Proposition 9

In period 2, a buyer bids $\pi(n) - \pi_l(n) - c_i$ for a good idea, and 0 for a bad one. Consider period 1. Waiting for period 2 to run an auction thus grants the seller an expected profit of $q[\delta_s(\pi - \pi_l - E[c_{n2}]) - \Delta]$.

In period 1, by contrast each buyer is ready to pay $q\delta_b(\pi - \pi_l - E[c_{n2}])$ for the license. Running an auction in period 1 thus grants the seller an expected profit $q\delta_b(\pi - \pi_l - E[c_{n2}])$.

So the seller runs an auction in period 1 iff:

$$\Delta \geq (\delta_s - \delta_b)(\pi - \pi_l - E[c_{n2}])$$

Bargaining in the second period

Consider the case where the innovator has developed the idea, which happens to be good. Assume that all negotiation have failed before the last sequence in the second period. Consider the bargaining session with the last buyer. If a license is signed at a price p, the buyer receives $\pi - p$ and the innovator p, whereas if the negotiation fails they respectively receive π_0 (as the current negotiation is the last one, no license will be signed if it fails) and 0. By Assumption, $\pi(n) - \pi_0(n) \geq 0$, and thus there is room for an agreement. The player that is drawn to make the offer receives the whole surplus from the trade. For the sake of simplicity, we assume that, when indifferent between accepting and rejecting an offer, a firm accepts it. If the buyer makes the offer, he offers $p^n_{2B} = 0$ and the seller accepts. If the seller makes the offer, he offers $p^n_{2S} = \pi(n) - \pi_0(n)$ and the buyer accepts.

Consider now the previous negotiation rounds in the second period. We show the following recursive property:

$\mathbf{P_k}$: *If the negotiation with the kth buyer starts (with $k \leq n-1$), in the continuation equilibrium,*

- *Whenever the seller makes the offer, he offers a price $\pi(n) - \pi_l(n)$;*
- *Whenever the buyer makes the offer, he offers a price $p_{2B}^k = \frac{(\pi(n)-\pi_0(n))}{2^{n-k}} + (\pi(n) - \pi_l(n))(1 - \frac{1}{2^{n-k-1}})$.*

We first show this property for $k = n-1$. Consider the negotiation between the innovator and the buyer before last, assuming that all previous negotiations failed. When ε goes to zero, both firms anticipate that if they do not sign, bargaining with the last buyer will succeed: (expected) default options are thus $\frac{\pi(n)-\pi_0(n)}{2}$ for the seller and $\pi_l(n)$ for the buyer. Thus

- If the seller makes the offer, he offers a price $\pi(n) - \pi_l(n)$, which leaves the buyer indifferent between accepting a rejecting;
- If the buyer makes the offer, he offers $p_{2B}^{n-1} = \frac{(\pi(n)-\pi_0(n))}{2}$, which leaves the seller indifferent between accepting and rejecting.

In each case, the offer is accepted. Therefore, property P_{n-1} is correct.

$\mathbf{P_{k+1}} \Rightarrow \mathbf{P_k}$: Consider the negotiation with the kth buyer. Because of property P_{k+1}, the buyer and the innovator know that a license will be signed with the next buyer in the sequence, if they fail to agree. The disagreement points are $\frac{1}{2}[\pi(n) - \pi_l(n) + \frac{(\pi(n)-\pi_0(n))}{2^{n-k-1}} + (\pi(n) - \pi_l(n))(1 - \frac{1}{2^{n-k-2}})]$ for the innovator and π_l for the buyer. Thus

- If the seller makes the offer, he offers a price $\pi(n) - \pi_l(n)$, which leaves the buyer indifferent between accepting a rejecting;
- If the buyer makes the offer, he offers $p_{2B}^k = \frac{(\pi(n)-\pi_0(n))}{2^{n-k}} + (\pi(n) - \pi_l(n))(1 - \frac{1}{2^{n-k-1}})$, which leaves the seller indifferent between accepting and rejecting.

In both cases the license is indeed signed. We have thus shown that P_k is correct.

The result stated in Proposition 1 is property $\mathbf{P_k}$ for $k = 1$.

Bargaining in the first period

Note first that if $\Delta > p_2^g$, then if no license is signed in the first period, the innovator does not develop the product. Thus, when the innovator negotiates with the last buyer in the sequence in period 1, her outside option is zero. Bargaining will therefore necessarily succeed in period 1. For the rest of the proof we thus concentrate on the case $\Delta < p_2^g$.

Step 1: If the condition of Proposition 2 is satisfied then, in all PBNE, a license is signed in the first period

Suppose there exists a PBNE such that the license is signed in period 2. We know in period 2, bargaining immediately succeeds if the innovation is good.

Consider the last bargaining session in period 1. As we are in a PBNE, beliefs are consistent on the equilibrium path, therefore the buyer believes the technology is good with probability q. The expected payoff of the seller if the negotiation breaks is thus $p_2^g - \Delta$, while the expected payoff of the last buyer in the sequence id $q\pi_l + (1-q)\pi_0$.

If the buyer is drawn to make the offer, the minimum price he can offer such that the seller accepts the offer is $p_{1B}^n = p_2^g - \Delta$. It leaves him with a profit higher than its outside option if $p_{1B}^n \leq q(\pi - \pi_l)$, that is, if $\Delta \geq p_2^g - q(\pi - \pi_l)$: this condition is satisfied by assumption therefore if the buyer is drawn to make an offer, the last buyer in the sequence deviates in the first period and a license is signed.

If the seller is drawn to make the offer, the highest price he can ask such that the buyer accepts is $p_{1S}^n = q(\pi - \pi_l)$. It leaves him with a profit higher than its outside option if $p_{1S}^n \geq p_2^g - \Delta$, that is, if $\Delta \geq p_2^g - q(\pi - \pi_l)$: this condition is satisfied by assumption therefore if the seller is drawn to make an offer, the last buyer in the sequence deviates in the first period and a license is signed.

There is therefore no PBNE where the license is signed in period 2 since we can always construct a profitable deviation.

Step 2: If the condition of Proposition 2 is not satisfied then in all PBNE, the license is signed in the second period

Consider a PBNE. Consider the last bargaining session in period 1 when the innovator has negotiated with all but one buyer. Suppose the beliefs of the last buyer are that the innovator is of a good type with probability q'.

First, in all equilibria, $q' = q$. Indeed, given that there is an exogenous probability of breakdown η before each session, a bargaining session between the innovator and the last buyer in the sequence is on the equilibrium path regardless of the equilibrium. Therefore, the last buyer does not update his beliefs based on the fact that the innovator comes to him.

If the innovator is drawn to make the offer, the highest price he can ask such that the buyer accepts is $p_{1S}^n = q(\pi - \pi_l)$. It leaves him with a profit higher than its outside option if $p_{1S}^n \geq p_2^g - \Delta$, that is, if $\Delta \geq p_2^g - q'(\pi - \pi_l)$: this condition is not satisfied by assumption therefore if the seller is drawn to make an offer, he does not make an acceptable offer to the last buyer in the sequence.

Similarly, if the buyer is drawn to make the offer, the lowest price he can offer such that the seller accepts is $p_{1B}^n = pp_2^g - \Delta$. It leaves him with a profit higher than its outside option if $p_{1B}^n \leq q(\pi - \pi_l)$, that is, if $\Delta \geq p_2^g - q(\pi - \pi_l)$: this condition is not satisfied by assumption therefore if the buyer is drawn to make an offer, the last buyer does not make an acceptable offer to the seller.

Therefore if the condition of Proposition 2 is not satisfied, in any PBNE no license is signed in the subgame where the innovator negotiates with the last buyer in the sequence. In any PBNE, when the innovator bargains with the buyer who is the one before last in the random sequence, both know that the negotiations will fail in the last round of negotiations in period 1. The continuation values are then identical to those of the last and we find that the same condition applies to all potential buyers but the first one in the sequence. The outside option of the first potential buyer to negotiate is higher than that of his competitors, as he anticipates that he will be the one who signs a license in the second period: he therefore has even less incentives to buy a license in the first period than his competitors. Reasoning recursively we can conclude that if the condition is not satisfied, no agreement can be reached in period 1.

Cost reducing innovation under Cournot competition

Assume that the n buyers initially produce a homogenous good at the same constant marginal cost c. They compete in quantities and demand is assumed to be linear: $D(p) = 1 - p$, where p is the price of the good. The outcome of a good type innovation is a new process that reduces the production cost to zero (a bad innovation does not modify the production cost). We also assume that the innovator's outside option is $\kappa = 0$.

The initial profits on the product market are $\pi_0(n) = \frac{(1-c)^2}{(n+1)^2}$. Signing a license for a good innovation results in asymmetric competition, as the cost of the licensee is lower than that of his competitors. If the innovation is good, the licensee thus receives $\pi(n) = \frac{(1+c(n-1))^2}{(n+1)^2}$ whereas his competitors receive $\pi_l(n) = \frac{(1-2c)^2}{(n+1)^2}$. Given these payoffs, Assumption 1 holds. Note that the innovation is drastic and the licensee becomes a monopoly if $c \geq \frac{1}{2}$. We only consider the more interesting case where $c < \frac{1}{2}$.

We can show that the condition of Proposition 4, $\pi'(n) \leq \pi'_l(n)$, is satisfied in this case. Therefore, for large values of n, the efficiency threshold $\underline{\Delta}(n)$ decreases in n (the condition for signing a license is easier to meet). Straightforward comparative statics reveal that the threshold decreases in q, and can even become negative for low values of n, in which case a license is always signed in the first period. Figure 2 plots the threshold in the case $c = 0.1$ for several values of q. The threshold has an inverted U-shape in n.

Proposition 7

In the second period, the type of the innovator is revealed. Buyer i bids $\pi_H - \pi_l - c_i$ for a good innovation and $\pi_L - \pi_l - c_i$ for a bad one. In both cases, trade occurs. Therefore the expected payoff of an innovator if he waits for period 2 to run an auction is $\pi_H - \pi_l - E[c_{n2}] - \Delta$ for a good innovator and $\pi_L - \pi_l - E[c_{n2}] - \Delta$ for a bad one.

First, there exists a pooling equilibrium where both types of innovators run an auction in period 1 if and only if $\Delta \geq (\pi_H - \pi_L)(1 - q)$. In such an equilibrium, buyers anticipate a good innovation

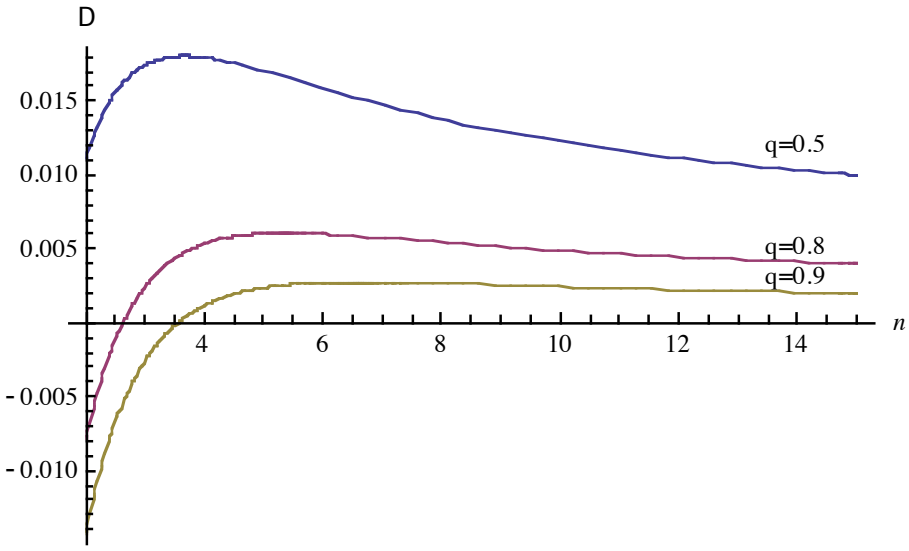


Figure 2: Cournot $c = 0.1$

with probability q, so each of them bids $q\pi_H + (1-q)\pi_L - \pi_l - c_i$. The expected payoff of an innovator if he runs an auction in period 1 is $q\pi_H + (1-q)\pi_L - \pi_l - E[c_{n2}]$ irrespective of its type. It is profitable for a good type to deviate and wait for period 2 iff $\Delta \leq (\pi_H - \pi_L)(1-q)$, while this deviation is never profitable for a bad type. So there is an equilibrium where both types run an auction in period 1 iff $\Delta \geq (\pi_H - \pi_L)(1-q)$.

Assume now that $\Delta \leq (\pi_H - \pi_L)(1-q)$. There exists a separating equilibrium where the bad type runs an auction in period 1, while the good type waits for period 2. In this equilibrium, if an auction is run in period 1, bidders revise their priors and believe that the innovator is bad. Each buyer bids $\pi_L - \pi_l - c_i$, and the expected payoff of the seller is thus $\pi_L - \pi_l - E[c_{n2}]$, which is higher than the expected payoff of a bad type if he waits for period 2 to run the auction, but lower for the high type.