Inefficiencies in technology transfer: theory and empirics*

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Abstract

Markets for technology can promote innovation by allowing for division of labor in research and development. Some firms may specialize in the discovery of ideas, while others have a comparative advantage in later stages of development and marketing. However, these gains depend on the timing of technology transfer: the buyer of an idea should assume development at the stage at which he has an efficiency advantage. We show that in an environment with asymmetric information about the value of the idea and where this asymmetry decreases as the product is developed, technology transfer happens later than is socially optimal. We obtain a condition for the optimal timing to take place, and show that the intensity of competition between potential buyers has countervailing effects on this condition. Empirical analysis of licensing contracts signed between firms in the pharmaceutical industry confirms our theoretical predictions.

Jel Codes: L13, L24, L65, O32.

Keywords: Innovation, Licensing, Market structure, Bargaining, Pharmaceuticals, Biotechnology.

1 Introduction

Innovation is undeniably an essential engine of growth. By allowing for specialization in the different phases of research and development, markets for technology are thought to improve the efficiency of the innovative process. They have grown in importance over recent decades, as licensing has become an increasingly popular means of transferring ideas.[1] We argue in this paper that these efficiency gains crucially depend on the timing of exchange, i.e. the phase at which the R&D project is transferred from one firm to another. We identify, both theoretically and empirically, factors that may distort technology transfer and reduce the productivity of R&D. In particular, we explore the relationship between market structure and the efficiency of technology transfer.

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[1]Estimates of the size of the global market for technology range from $5.6 billion during the 1980s to $36-100 billion by the late 1990s.

Whereas innovation has often been viewed, particularly in the theoretical literature, as a "black box" inside a vertically integrated firm, specialization in different phases of the innovation process is common in many industries, such as the pharmaceutical, chemical and semiconductor sectors (Arora et al. (2001)).[2] Ideas are generally transferred from early stage innovators to later stage developers through licensing contracts. This division of innovative labor may increase the efficiency of the innovation process, depending on the timing of the technology transfer. For instance, consider two firms, one more efficient in conducting early stage research and the other more efficient in the final stage. It is socially optimal to have the relatively efficient firm own the idea at each stage, i.e. to transfer the invention from the first to the second firm at the end of the initial stage. Any other timing increases the cost of innovating and might lead to the innovation being abandoned. The innovation rate thus crucially depends on the timing of technology transfer.

We focus on two frictions that are typical in many innovative industries and that may create deviations from the socially optimal timing of transfer in markets for technology. First, innovative environments are often characterized by asymmetric information. The innovator is usually better informed about the value of her idea than a potential buyer. Second, as research progresses, verifiable information about the underlying value of the idea is revealed and the information asymmetry shrinks. We show theoretically that these two conditions can lead to delays in technology transfers. We test several predictions of our model using data on licensing of drug development projects.

The pharmaceutical industry is indeed a very good illustration of the process we described. There appears to be an increasing division of labor between small biotechnology firms and large pharmaceutical companies.[3] 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.[4] 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.

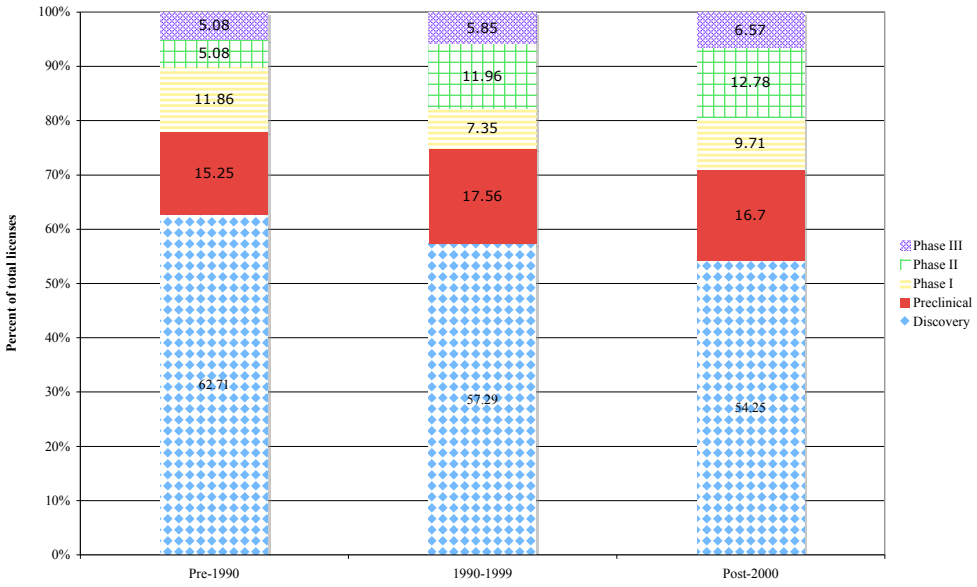
Figure 1 illustrates that in this industry, the fraction of licensing contracts signed after the discovery and preclinical stages has increased by more than 30% since 1990, a period also characterized by low numbers of new drugs launched. These delays do not merely reflect an increase in the total time required for drug development; rather, the technology transfer is

[2]There are of course notable exceptions, including Silveira & Wright (2010), who focus on liquidity concerns in a model of the division of labor between innovators and entrepreneurs.

[3]Both the academic literature and the popular press note that a significant proportion of the drugs marketed by major pharmaceutical companies originate from licensing deals with smaller biotechnology firms: Angell (2004) claims that one third of the drugs marketed by major pharmaceutical companies originate from licenses with biotechs or universities, and 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).

[4]Guedj & Scharfstein (2004) show clear differences in the success rates of drug candidates in cancer between experienced, larger firms and small biotech firms. In an article in *Nature Reviews: Drug Discovery*, Kalamos & Pinkus (2003) claim that "[f]or the pharmaceutical industry, innovative biotech compounds have served to buttress lagging R&D productivity... pharma brings clinical development, portfolio management and commercialization skills that are lacking in many biotech companies."

Figure 1: Stage at licensing signing over time



occurring at later stages of development, after the completion of more advanced clinical trials. This delay in technology transfer also coincides with a period of increased market concentration, as the pharmaceutical industry has experienced substantial merger activity. The link between the number of potential buyers and the timing of technology transfer is one of the central considerations in this paper.

In a two period model involving one innovator and n potential buyers who compete on a downstream market, we examine the relationship between competition and the timing of technology transfer. Prior to the first period, the innovator has had an idea that requires additional development to bring it to market. While she faces some positive cost of development, development is costless for the buyers. It is thus socially optimal to transfer the idea from the innovator to one of the buyers in the first period. However, the first period is also characterized by asymmetric information: the innovator knows the value of her invention, but the buyers are uncertain whether the idea is good. Development efforts from the first to the second period reveal verifiable information about the value of the idea and the buyer's uncertainty is resolved prior to the start of the second period.

Innovations are transferred by signing contracts that transfer the full ownership of the innovation to the buyer. Such contracts correspond to an exclusive license or to the acquisition of the innovator's firm by the buyer. We build a bargaining model in which the larger the number of potential buyers, the greater the share of the surplus extracted by the innovator. In this framework, we identify a condition for the contract to be signed in the first period, and we examine how the number of competitors influences this condition. The key tradeoff is the

following: because the price of a license in the first period reflects buyers' uncertainty about the quality of the idea, an innovator who knows that her idea is good is tempted to wait for information about the idea's value to be revealed. However, she must incur development costs in order to do so. An agreement can therefore be reached in the first period only if the efficiency advantage of buyers in the development stage is large enough to offset the innovator's increase in the price she receives by waiting.

The number of potential buyers n affects this tradeoff in an ambiguous way. If profits on the downstream market do not depend on the number of buyers n, we find that an increase in the number of buyers unambiguously delays the transfer. An increase in n increases the bargaining power of the innovator and the price she can obtain in the second period. The innovator thus wants to wait, while the buyers want to sign earlier. The former effect is shown to dominate. 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. Greater competition increases the bargaining power of the innovator, but decreases the downstream profits obtained from the innovation. That is, the innovator obtains a larger slice of a smaller pie. For unconcentrated markets, the second effect dominates and the second period price decreases with the number of buyers, thus leading to earlier signing. The opposite is generally true for concentrated markets. Thus, we find an inverted U-shape for the effect of the number of competitors on the delay in licensing.

We also study a variant of the model in which we distinguish two types of firms: incumbents with existing products on the market and 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.

We develop a tractable bargaining model that allows us to examine the timing of technology transfers in an environment with asymmetric information. This model is based on sequential bargaining as in Stole & Zwiebel (1996) and Smith & Thanassoulis (2007), although we adapt the framework to include information asymmetries. Much of the existing literature on technology transfers under asymmetric information when intellectual property rights are weak or non existent (in particular Anton & Yao (2002)) examines 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 the innovator has no means to credibly disclose information about the value of the invention.

Our empirical analysis of licenses in the pharmaceutical industry confirms the model's predictions. We combine data on licensing deals and the stage of drug development at signing with data on the number of firms in different therapeutic classes (firms with drugs treating similar diseases) who compete on the downstream 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. 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.

A key assumption in the theoretical model is that the innovator is better informed about the quality of the idea than the buyers. Indeed, in the absence of asymmetric information, competition has no effect on the timing of transfers in our model. In the empirical analysis we examine subsets of the data based on criteria related to the extent of asymmetric information about the quality of innovators and their ideas. We find that the effect of the number of entrants and incumbents on delay is insignificant for the "low asymmetry" subsets and significant for the "high asymmetry" subsets, which is consistent with the model's prediction on the relationship between competition and information asymmetry.

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)).[5] However, with the exception of Gans et al. (2008), the question of the timing of licensing has been left aside. Gans et al. (2008) point out that a number of reasons can lead to deviations from the socially optimal timing of technology transfers, including search costs, asymmetry of information and uncertain property rights. Gans et al. (2008) concentrate on the third explanation. 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. We focus instead on asymmetry of information, and we examine more specifically the impact of market structure on timing.

Though the question addressed in this paper is motivated by the particular application to the pharmaceutical industry, the theoretical model is quite general. The results should be relevant in industries with the following characteristics. First, there should exist some asymmetry of information between the innovator and potential buyers, a reasonable feature in most innovative sectors. Second, information should be revealed during the development of the invention. Third, there should be some specialization in the innovation process.[6]

The paper proceeds as follows. In section 2, we present the model and determine the main theoretical results in section 3. In section 4, we examine a number of robustness checks. We test these results on data on licensing contracts in the pharmaceutical industry in section 5 and 6. All proofs are presented in the appendix.

2 Model

We consider a model with $n \geq 2$ symmetric firms competing on a downstream market and one innovator with a pre-existing idea. The n firms are the only potential buyers of the idea from the innovator, and do not themselves attempt to innovate (for instance, because their cost of early stage innovation is very high). The idea can be transferred by signing a license or by direct acquisition of the innovator's firm. To be consistent with our empirical application, we will from now on use the term 'license' for the contract that transfers the ownership of the idea

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

[6] See Arora et al. (2001) for a discussion of specialization and the division of innovative labor.

from the innovator (that we sometimes call licensor) to one of the buyers (that we sometimes call licensee). This license transfers the full ownership of the invention in exchange for a fixed price that is determined by a bargaining process that we describe below. The license is exclusive: if the innovator and one particular buyer reach an agreement, no other license can be sold and the game ends.[7]

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 yet licensed the innovation, she needs to decide whether to develop the product further. Development of the innovation from period 1 to period 2 costs Δ for the innovator. The potential buyers are assumed to be more efficient in development. Specifically, we assume that the cost of development for a buyer is zero. Δ thus represents the difference in efficiency between the innovator and buyers. As pointed out in the introduction, 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. Δ measures this difference in efficiency. Second, the information structure differs between period one and two. Period 1 is characterized by asymmetric information about the quality of the innovation. The innovator knows the quality of her idea, but none of the buyers do. They share a common prior that the innovation is of a good type with probability q or a bad type with probability $1-q$ [8] At the beginning of the second period, the type of the innovation is revealed. This is a result of the verifiable evidence generated during the development process.

2.1 Payoffs

The profits obtained from a good type innovation are described below in reduced form. In the two examples of section 3.2, we impose more structure.

- $\pi_0(n)$ 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 license a good type innovation, but should he fail to do so, he prefers that no rival licenses the innovation either. We also assume that all profit functions are weakly decreasing in n and are continuously differentiable.

We denote by κ the outside option of an innovator who has developed a good type innovation until the second period and has not sold a license. It represents profits that can be obtained from alternative uses. Note that if the innovation is not developed until the second period, it does not generate any profits. We impose the following assumption:

ASSUMPTION 1: $\pi(n) - \pi_0(n) > \kappa$

[7] Note that in the pharmaceutical industry, most contracts are exclusive. They involve the transfer of a single compound to a particular firm (in our data, more than 85% of the licenses are exclusive).

[8] In Allain et al. (2011), we examine the case where the innovator is overconfident about the value of her invention.

Assumption 1 states that if the quality of the innovation is known to be high, there are gains from trade between the innovator and a buyer. Indeed, if a license is sold, the aggregate profits of the negotiators are $\pi(n)$ while the aggregate profit without sale is given by $\kappa + \pi_0(n)$. No license would ever be sold without this assumption.

If the innovation is of a bad type, we assume that it does not generate any profits. The innovator cannot sell a bad type idea in period 2, and if she fails to sell the idea in period 1, she will not develop the idea from the first to the second period. The buyers, regardless of whether they sign a license, obtain their status quo payoff $\pi_0(n)$.

2.2 Bargaining

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.[9] If all bargaining sessions fail in the second period, the players obtain their outside options. Within a period, the innovator cannot restart 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 bargaining procedure inside a session occurs as in the alternating offer game with exogenous probability of breakdown introduced by Binmore et al. (1986). As in their paper, there is no discounting and the two players alternate making offers. If an offer is accepted, the game terminates. If it is rejected, the bargaining session breaks down exogenously with probability ϵ and the innovator moves to the next buyer in the sequence. If not, a new offer is made.[10] We also assume that with probability η, a bargaining session does not even start. That is, a breakdown can occur even before the start of a session.[11]

The information structure is as follows. 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 chose this model of sequential bargaining for a number of reasons. First, we are interested

[9] Redrawing the order across periods does not qualitatively affect our results: see Allain et al (2011).

[10] It is important that all bargaining sessions take a finite amount of time so that potentially all n sessions can take place before the end of period 1. As pointed out by Stole & Zwiebel (1996), "one can think of alternating offers being made at times $t, t + \frac{1}{2}, t + \frac{2}{3}, ..., t + \frac{k-1}{k}$ to ensure that each bargaining session ends with probability 1 in one unit of time."

[11] Note that we could have assumed $\eta = \epsilon$, but we prefer to use a different notation to emphasize the different roles of the probability of breakdown. The consequences of this assumption can be illustrated in the following example: with probability $\eta^3(1-\eta)$, the innovator cannot make an offer to the first three buyers in the sequence and so makes his first offer to the fourth buyer. This assumption will prove essential to limit the multiplicity of equilibria, as discussed in section 3.1.2.

in examining how competition influences the timing of licensing. We show that, in this sequential model, the larger the number of potential buyers in the sequence, the higher the price extracted by the innovator. Most models of oligopsony do not capture such an effect of the number of buyers on price.[12] Second, while an auction model where the bidders have heterogenous values yields similar results (see section 4.1),[13] it does not fit our empirical application well. Indeed, our model of bargaining appears to be a good representation of the process through which licenses are sold in the pharmaceutical industry. Negotiations typically involve an exclusive period during which the licensor may not hold discussions with any other potential licensee.[14]

Our model builds on other models of sequential negotiations, in particular Stole & Zwiebel (1996), who examine bargaining over labor inputs.[15] An important difference from the previously mentioned literature is that we assume that licenses are exclusive.[16] This assumption is not only realistic, but also necessary for tractability, since we introduce an essential feature to the model: asymmetric information. Despite this additional complexity added to the model, we are able to unambiguously predict the timing of technology transfer.

An important characteristic of our model is that the innovator holds private information on the value of the innovation. There is a large literature on bargaining under asymmetric information, summarized in Ausubel et al. (2001). Models in that literature typically consider bargaining protocols with discounting between offers. Under certain assumptions that limit the large multiplicity of equilibria, the seller faces the following trade-off: delay the sale to screen the different buyer types or sell earlier at a lower price.[17] Our focus is not on delay in bargaining *within* a bargaining session, but rather on delays *between* the two periods. We therefore consider a bargaining model with an exogenous risk of breakdown of the negotiation but without discounting (following the alternating offer model of Binmore et al. (1986)). Without such discounting, the trade-off previously mentioned is not relevant. Furthermore, we do not attempt to characterize the full set of equilibria. Instead, we prove a property for timing that is common to all equilibria.

[12]For instance, if the innovator made take-it-or-leave-it offers, n would not influence the bargaining power of the innovator, the innovator would extract the full surplus regardless of n. Note also that if the buyers made simultaneous offers to the innovator, competition between them for an exclusive license would leave them with no rents, independent of their number (as long as $n \geq 2$).

[13]In this case, a larger n mechanically increases the expected value of the highest valuation and thus the amount extracted by the seller.

[14]Press releases such as this are common: "Micrologix Biotech Inc. has entered into an exclusive negotiation period to license MBI-226, an antimicrobial cationic peptide in Phase III clinical development for the prevention of catheter-related infections, to a US-based specialty pharmaceutical company ("Specialty Pharma"). The negotiation period is for up to 60 days (the "Exclusivity Period") during which Micrologix will negotiate exclusively with Specialty Pharma the terms of a definitive license agreement for MBI-226." (http://www.secinfo.com/d12MGs.1n4.htm)

[15]In Stole & Zwiebel (1996), workers are also ordered in a sequence. In a bilateral negotiation, if a worker agrees to a wage, the firm moves on to the next worker in the sequence. However, these agreements are not binding. If there is a breakdown in a later negotiation, this triggers a replaying of the sequence between the firm and each remaining worker. This additional complexity does not arise in our framework because of the exclusivity of licenses. See also Smith & Thanassoulis (2007) and Raskovich (2007).

[16]For instance, in Stole & Zwiebel (1996), the firm may contract with multiple workers. Considering non-exclusive licenses could modify our result. De Fontenay & Gans (2005) provide a complete study of the outcome of negotiations with interlocking relationships between buyers and sellers and externalities among the buyers.

[17]The multiplicity is reduced by the assumption of stationarity introduced inFudenberg et al. (1985). Drugov (2006) considers a single take it or leave it offer in each period and faces the same tradeoff. This setting also limits the number of equilibria and allows to focus on the effect of an exogenous signal on the timing of contracting.

3 The timing of technology transfer

The socially optimal timing is to transfer the innovation from the innovator to the buyer in the first period, as development is costless for buyers. We show in this paper that asymmetric information on the value of the innovation can delay the transfer. We solve the game by backward induction. All the results are limit results as the probabilities of exogenous bargaining breakdown ϵ and η converge to zero. The appendix contains all proofs.

3.1 The bargaining game

3.1.1 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. We define $p_2(k)$ as the price of a license in second period when there are k buyers left in the sequence with whom the innovator has not yet negotiated.

Consider the negotiations with the $(n-k)$th buyer (k buyers left in the sequence). We first focus on the case $k \geq 1$ and discuss the case of the last buyer separately. If the negotiations are successful, the innovator obtains the price of the license $p_2(k)$ and the buyer $\pi - p_2(k)$. As shown in Binmore et al. (1986), the outcome of the bargaining game when the probability of breakdown ϵ converges to zero is given by the Nash bargaining solution with the disagreement points equal to payoffs following breakdown.

In our setting, the payoffs in case of breakdown are determined by the outcome of the remaining negotiations. If an agreement is expected to be signed with the next buyer in the sequence, the innovator can expect the price $p_2(k-1)$ while the buyer expects profits π_l (the profits of a buyer if a license is signed by one of his competitors). This determines the following recursive relationship for $k > 1$:

$$p_2(k) - p_2(k-1) = \pi - p_2(k) - \pi_l \tag{1}$$

Under Assumption 1, the expectation that bargaining will succeed with the next buyer in the sequence is correct. Indeed, Assumption 1 ($\pi(n) - \pi_0(n) > \kappa$) guarantees that there are gains from trade with the last buyer. A 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. The outside option of the seller in the sequence of negotiations decreases by construction: $p_2(k) > p_2(k-1)$, as each buyer has to leave the seller a higher rent than the next potential buyer. Thus, as shown in the following Proposition, an agreement is reached with the first buyer in the sequence.

PROPOSITION 1: *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 at a price:*

$$p_2(n) = \left(\frac{1}{2}\right)^n (\kappa + \pi_l - \pi_0) + \left(1 - \left(\frac{1}{2}\right)^n\right)(\pi - \pi_l) \tag{2}$$

Note that the price $p_2(n)$ is increasing in n. A larger number of buyers in the sequence allows the innovator to extract a larger share of the surplus.

3.1.2 Bargaining in the first period

In the first period, bargaining is more complex due to the information asymmetry between the innovator and the buyers. We show that all Perfect Bayesian Nash Equilibria (PBNE) share a common property that allows us to determine the equilibrium timing of licensing.

PROPOSITION 2: *In all PBNE, a license is sold in the first period if and only if the following condition is satisfied:*

$$q(\pi - \pi_l) \;\geq\; p_2(n) - \Delta \tag{3}$$

To understand the mechanics of the negotiation, it is useful to consider the last bargaining session in period one. Given Proposition 1, all players know that bargaining will ultimately succeed in the second period if the idea is good. However, an innovator only develops the product if the expected profits can cover the cost Δ: if $p_2(n) < \Delta$, the innovator never develops the invention herself. Her outside option at the end of bargaining is then zero, and a mutually beneficial agreement can always be found in the first period.[18]

We now consider the last bargaining session and the offer made by the innovator in the case where $p_2(n) \geq \Delta$. A good innovator will never offer a price less than $p_2(n) - \Delta$, as she can guarantee herself a price of $p_2(n)$ in the second period at a cost of Δ. A bad innovator wants to mimic the good type, and thus requests the same price. If the buyer accepts the offer and believes the probability of facing a good type innovator is still q,[19] his expected utility is $q\pi + (1-q)\pi_0$. However, he can always guarantee himself his outside option, given by $q\pi_l + (1-q)\pi_0$. Indeed, if he waits until the second period, he knows that a contract will be signed with the first buyer in the random sequence if the innovation is good and he will therefore obtain π_l.

We focused in the previous discussion on the last buyer in the sequence. If the last potential buyer is expected not to sign, the one positioned just before the last in the sequence finds himself in an identical situation as the last and will therefore not sign either. The only potential buyer with a different perspective is the first in the sequence: his outside option 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 incentive to buy a license in the first period than his competitors. The condition for early signature is thus determined by the incentives of the last buyer in the sequence.

If the condition is satisfied, the socially optimal timing of licensing is achieved: technology transfer takes place in the first period and the more efficient buyer develops the innovation. However, for low values of the probability of facing a good type q or of the efficiency difference Δ between the innovator and the buyers, the threshold for early signature is more difficult to

[18] Note that, for a similar reason, an innovator with a bad idea would never wait for the second period if her innovation generated strictly positive profits (and thus a positive price in the second period). In such a case, there exist pooling equilibria where a license is signed in the first period when Δ is high, and separating equilibria where the good innovator signs in the second period and the bad innovator signs in the first period for low Δ (proof available upon request).

[19] In equilibrium this belief is correct.

meet and late (and inefficient) signature is more likely. The condition of Proposition 2 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

$$\underline{\Delta}(n) \equiv p_2(n) - q(\pi - \pi_l). \tag{4}$$

In the following sections, 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.[20]

It is important to point out that one particular assumption limits the multiplicity of equilibria. We assume that before the start of each individual bargaining session, there is an exogenous risk of breakdown with probability η. Therefore, regardless of the equilibrium that we consider, starting negotiations with any buyer in the sequence is always on the equilibrium path.[21] Thus, in all equilibria, all buyers start negotiating with the same belief q that the innovator is of a good type: the fact that the innovator approaches a buyer positioned late in the sequence does not change that buyer's belief about the innovator's type. In other words, the buyer does not interpret this fact as an endogenous breakdown of prior negotiations that might indicate he is facing a bad type.

Note that delays are always inefficient in our framework because we assume a zero cost of development for the buyer. Allowing for the buyer to face a positive cost of development $\delta < \Delta$ could mitigate the welfare effects of a delay in licensing, as the buyer would waste resources in developing an idea if he bought a bad type idea (which would happen with probability q). However, as long as the buyer has a significantly lower cost of development, $\delta < q\Delta$, welfare remains higher in any equilibrium with signature in the first period than in any equilibrium with signature in the second period. Even if the total development cost of the buyers does not satisfy this condition, it is sufficient to assume that any buyer can incur a minor cost $\delta' < q\Delta$ to observe the quality of the innovation before sinking the large development costs.

3.2 The effect of market structure

In this section, we examine how the number of buyers in the market n affects the condition of Proposition 2 and thus the timing of licensing. n may influence both the bargaining power of each player and the downstream profits.

3.2.1 Profits do not depend on n

As a benchmark, we begin with the case where the profits $(\kappa, \pi_l, \pi_0, \pi)$ 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 bargaining power of the buyers and of the innovator.

[20] Note that we could have considered a variation of the model where Δ would be drawn in a certain interval. An increase in $\underline{\Delta}(n)$ would then increase the probability of late signing.

[21] For example, suppose that an equilibrium is such that a license is signed with the third player. In equilibrium, the fourth player might still negotiate if negotiations do not even start with the third player (an event that occurs with probability η).

According to our results in section 3.1, in this particular case, the price of the license in the second period $p_2(n)$ increases with n. Indeed, when the innovator negotiates with the first buyer in the sequence, she can extract a larger share of the surplus since her outside option is now larger. The following proposition states that the effect of n on the timing of licensing is also unambiguous in this case.

PROPOSITION 3: *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 bargaining power of the innovator increases in the second period and therefore $p_2(n)$ increases. The innovator with a good idea has a greater incentive to wait to sign a license. Furthermore, as n increases, the expected profit in the second period is unchanged for all buyers except the first in the sequence. As we saw in the previous section, only the incentives of buyers *later* in the sequence determine the condition to sign early. Thus, overall, an increase in n will delay signature.[22] We show in the next section that the results may be different if the number of competitors impacts downstream profits in addition to bargaining power.

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 second period price. On the one hand, it raises the bargaining power of the innovator, who gets a larger share of the pie. On the other, it decreases the actual profits derived from the innovation, so the size of the pie shrinks. The tension between these two effects on the second period price yields an ambiguous effect of n 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 obtain a limit result for large values of n that is valid under a minimal condition on payoffs.

PROPOSITION 4: *If $\pi'(n) \leq \pi'_l(n)$, then for sufficiently large values of n, 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. As the number of buyers becomes large, the innovator enjoys all the bargaining power and can extract all the surplus in the second period. From Proposition 2, the price in the second period approaches $\pi(n) - \pi_l(n)$ for large values of n. So if $\pi'(n) \leq \pi'_l(n)$, the price decreases in n and licensing delays become less likely.

The condition for Proposition 4 is that an increase in the number of firms in the market n has a larger negative impact on the profits of a firm that signs a license ($\pi'(n)$) than on a firm that does not sign ($\pi'_l(n)$). This property is satisfied in the applications of Cournot and Bertrand competition that we describe below.

[22] This result extends to the case where the order is redrawn in the second period; see Allain et al. (2011).

Proposition 4 provides an unambiguous result for very competitive markets: licensing delays become less likely as n increases. For small values of n, however, the opposite result may hold, leading to an inverted U-shape for the relationship between number of competitors and delays in technology transfer. We examine two cases that illustrate this point, one involving a process innovation and the other a product innovation, to demonstrate that this result holds for more than the specific industry application we emphasize in this paper.

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.[23] 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.

Bertrand competition with differentiated products

Consider another example based on a differentiated goods model. Assume that the n buyers initially sell n symmetrically differentiated goods with a constant marginal cost c. 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

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

where q_i is the quantity of good i consumed, μ is the degree of product substitution between the goods ($\mu \in [0, +\infty]$) and v is positive and larger than c. The demand for each good is thus:[24]

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

[23] Note that, in the Cournot equilibrium, the variation of individual output following the entry of a new competitor is the same for all firms, licensee or competitor (here, $\frac{\partial q}{\partial n} = -\frac{1-2c}{(1+n)^2}$). Yet the resulting decrease in profit is larger for the licensee as its margin is higher.

[24] Note that in this model, aggregate demand is independent of the substitution between the products, and does not change with the number of products if all prices are equal.

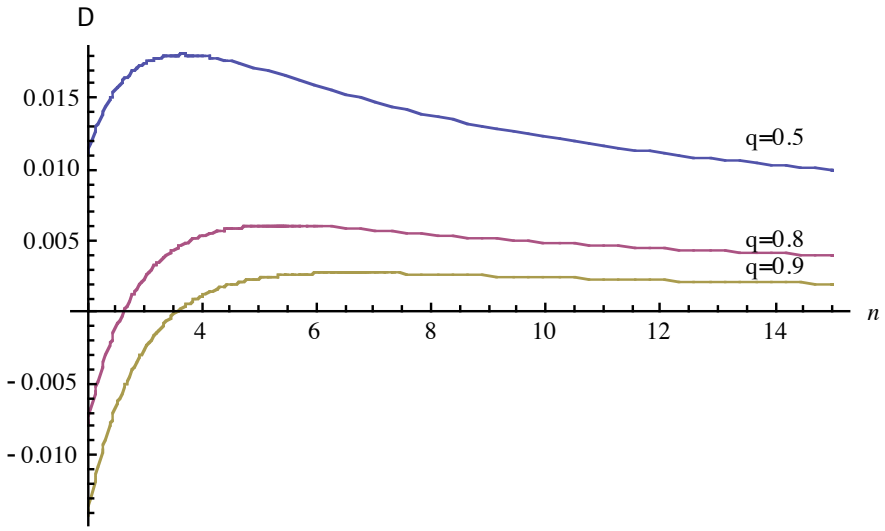


Figure 2: Cournot $c = 0.1$

The innovation corresponds to 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. We derive the equilibrium prices and profits in the Appendix. We keep the assumption $\kappa = 0$, so that Assumption 1 holds. Figure 3 plots the efficiency threshold for $c = 0.1, \mu = 0.5$ and $v = 1$ for several values of q. Though the sufficient condition of Proposition 4 is not always satisfied, the efficiency threshold has an inverted U-shape in the example we give.

3.2.3 Entrants and incumbents

Our previous analysis assumed that all potential buyers are symmetric. In reality, of course, the value of a license may differ across buyers for many reasons. In this section, we allow for some heterogeneity of buyers: some potential buyers have existing products that would compete with the licensed innovation, while others don't. Distinguishing between these two types of firms is important for our empirical analysis. Formally, we assume that there are n incumbents denoted by $i \in \{1, ..., n\}$ and e potential entrants denoted by $j \in \{1, ..., e\}$. Entrants are not active on the market prior to the innovation, but they may purchase the license and thus enter the market.

The potential entrants are all symmetric. Their outside option, regardless of whether someone else buys a license, is zero (since they have no existing products on the market and we don't take into account their profits on other markets). We denote by π_e the profit of an entrant who

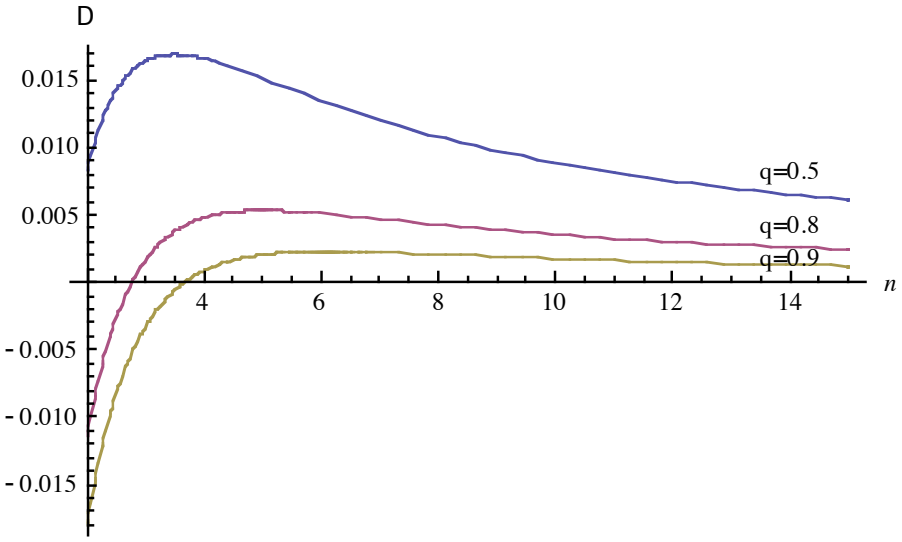


Figure 3: Bertrand $c = 0.1$, $\mu = 0.5$, $v = 1$

buys the license. For simplicity, we assume that $\kappa = 0$. The profits of the incumbents are, as in the previous sections, π if they get the license and π_0 if no one buys a license. However, the profit of an incumbent if someone else buys the license now depends on the identity of the buyer, since a new entrant increases the number of competitors. We denote these profits π_l if the buyer is another incumbent and π_{le} if the buyer is an entrant.

To keep the theoretical analysis tractable, we assume that the incumbents and entrants are "grouped" in the bargaining sequence. In other words, we consider two cases: either the innovator first bargains sequentially with all the entrants and then with all the incumbents, or the order is the reverse. We also assume that players are ordered in the bargaining sequence in such a way that the players with higher valuation bargain first: if $\pi_e < \pi$ (resp. $\pi_e > \pi$), the entrants are positioned later (resp. earlier) than the incumbents.[25] We present here the results in the case where the entrants bargain first. The results are qualitatively similar in the other case (see Allain et al. (2011)).

PROPOSITION 5: *All PBNE have the following properties:*

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

2. *The effect of the number of incumbents n on the efficiency threshold can be ambiguous. However, when the number of entrants e is large enough, $e > \widehat{e}$, the efficiency threshold*

[25] We assume as before that the order of bargaining is the same in the first and second period.

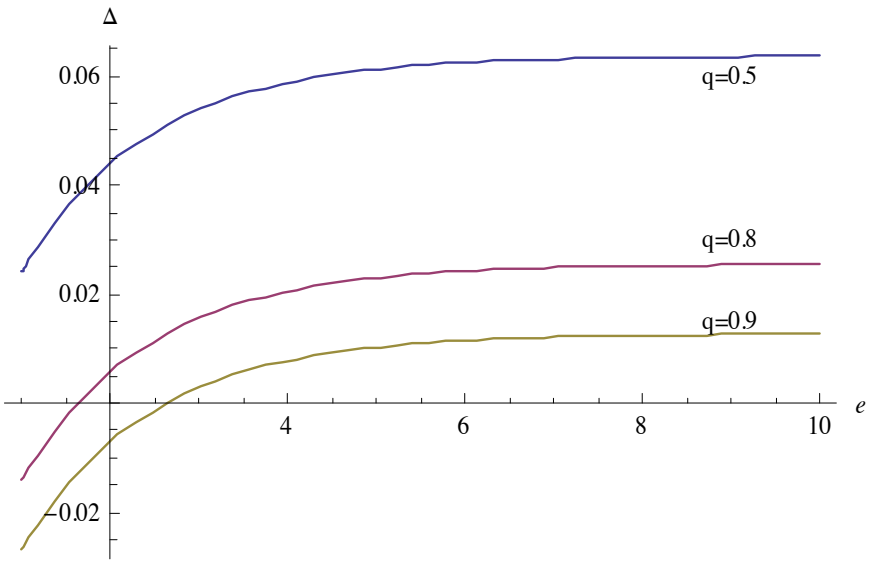


Figure 4: Effect of e for $n = 5$

unambiguously decreases with n (the condition for early signing is easier to meet).

Part 1 of Proposition 5 echoes Proposition 3. The number of entrants affects bargaining power, but not profits on the downstream market (as at most one of them will in the end be present on the market). Part 2 of Proposition 5, on the other hand, is a reflection of the case considered in section 3.2.2. The effect of the number of incumbents on the timing of licensing is potentially ambiguous as it affects both bargaining power and downstream profits. However, if the number of potential entrants is large enough, an increase in the number of incumbents unambiguously reduces licensing delays.

To illustrate this more clearly, we consider a variant of the cost-reducing process innovation under Cournot competition studied in the previous section. To ensure that $\pi_e > \pi$, we assume that the potential entrants are more efficient than the incumbents, namely that the innovation allows them to cut costs more significantly: if he signs a license, an entrant produces the good at zero cost, whereas the license only reduces an incumbent's cost from c to $\frac{c}{2}$. Following the logic of the example, the profit of an incumbent if one of the entrants gets the license is the profit when facing $n+1$ competitors $\pi_{le} = \frac{(1-2c)^2}{(n+2)^2}$, while the profit of the entrant is $\pi_e = \frac{(1+cn)^2}{(2+n)^2}$. In this context we plot the efficiency threshold for $c = 0.3$.[26]

Figures 4 and 5 illustrate Proposition 5. First, the efficiency threshold is increasing in e. Second, the effect of n tends to decrease the efficiency threshold except for small values of n and high values of q. When e is larger, the increasing portion is even smaller. In our

[26]For this value, the innovation is not drastic and $\pi_e > \pi$.

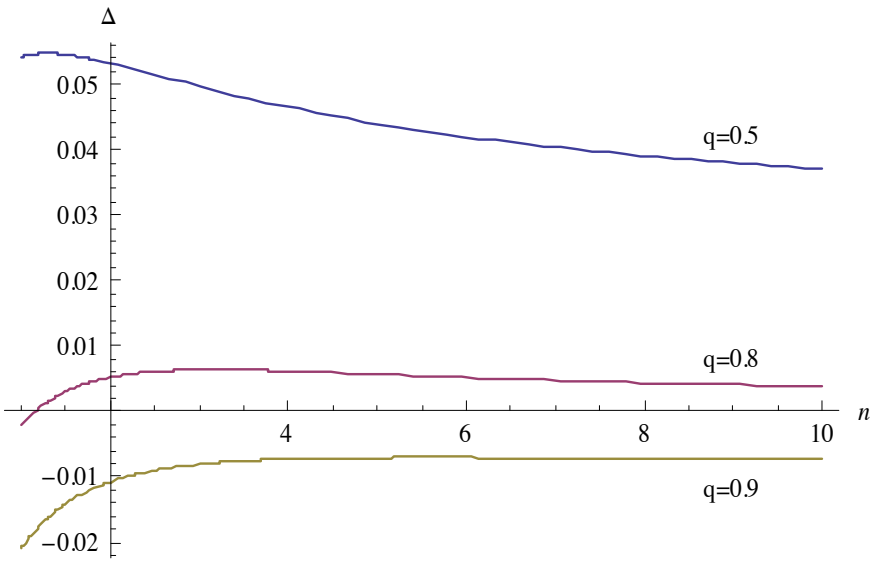


Figure 5: Effect of n for $e = 2$

empirical exercise, we will therefore examine the linear effect of e and n on timing and establish if an increase in the number of entrants e or a decrease in the number of incumbents n delays licensing.

3.3 The role of asymmetric information

A key assumption we make in the model is that there is asymmetric information between the licensor and potential licensees in the first period. We discuss in section 5 evidence in support of this assumption for the particular case of the pharmaceutical industry. In this section we argue that in the case of symmetric information, there are no deviations from the optimal timing of licensing. Thus, our results can also be seen as indirect evidence of the existence of asymmetric information between licensors and licensees.[27]

Suppose that both the innovator and the buyers are uncertain about the quality of the invention and both share the same belief that the type is good with probability q. Bargaining in the second period remains unchanged. In particular, given Assumption 1 ($\pi - \pi_0 \geq \kappa$), an agreement is always reached if the innovation is of the good type. However, in the first period, the innovator is now uncertain about the quality of her invention. In this case we obtain the following result.

[27] In section 6.3 we show empirically that in cases where we expect asymmetry of information to be high, the effects of the number of buyers is significant and of the expected sign, whereas there is no significant effect of a variation in number of entrants or incumbents in the low asymmetry cases.

PROPOSITION 6: *If the innovator and the buyers share the same belief q that the innovation is good, a license is always signed in the first period for all values of q and n.*

If an agreement can be reached in the second period (i.e., Assumption 1 is satisfied), then an agreement will be reached in the first period regardless of the degree of uncertainty q and of the number of competitors n. The intuition is the following. If an agreement can be reached in the second period when the idea is good, then there is an even larger surplus that can be shared in the first period, since the buyers can develop the product at a lower cost than the innovator. That is, the innovator risks a greater loss from developing an idea that turns out to be bad than do the buyers, who have development costs of zero. With uncertainty and symmetric information, we find that the license is signed at the socially optimal time.

In Allain et al. (2011), we present a different interpretation of our model. Our result for the effect of competition on the timing of licensing is also valid in the absence of asymmetric information if the licensor and the licensees have different beliefs about the probability of success in the first period. A typical example is the case of overconfident innovators. We show that such a model will lead to similar predictions.

4 Robustness and Extensions

4.1 Model of auctions

As we previously pointed out, few oligopsony models capture the effect of competition between potential buyers on the price of an exclusive deal. One exception is the following model of auction. We show that it yields the same type of results as our bargaining model.

We consider a model where in both periods the innovator can choose to run a second price auction with a reservation price. If she does not run an auction in the first period, or if she runs an auction but fails to sell the license because the reservation price is not met, she can choose to pay the cost Δ (known to all players) and develop the product herself. We suppose that the profits that can be obtained from a good type innovation are identical for all buyers and known to be $\pi(n)$. However there is a fixed cost of production c that is drawn for each buyer from a distribution $c \sim F$ with support $[\underline{c}, \overline{c}]$.[28] The fixed cost must be incurred after observing the value of the invention (it will be paid only if the idea is good). Specifically, the value to a buyer of a bad idea is 0, but $\pi(n) - c$ if the idea is good. For simplicity, we assume that $\pi(n) - \overline{c} > \kappa$ and that $\pi_l = \pi_0 = 0$.

We show in the Appendix that the unique bidding strategy for the buyers in both periods is to bid their expected value for the good.[29] Furthermore, the innovator will run an auction in the first period if and only the extra profit she expects from waiting do not cover the development cost Δ, as expressed in the following result:

PROPOSITION 7: *An innovator with a good idea runs an auction in the first period if and*

[28] Our auction is therefore one with private values. We need to have private values for the price to vary with the number of buyers.

[29] A buyer with cost c bids $q(\pi - c)$ in the first period and $\pi - c$ in the second period.

only if

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

where c_{n2} is the second lowest cost among the n buyers. Furthermore, if she runs an auction in the first period, she sets a zero reservation price and always sells a license.

We see that, if profits π do not depend on n, licensing delays become more likely as n increases. Indeed, the second period price mechanically increases as more draws are taken from the cost distribution. The same logic as in Proposition 3 then applies. The good innovator, who knows her quality, can fully extract this increase in the price in the second period. The buyers, though, only consider the added cost, corresponding to a higher price in period 2, if the innovator is good with probability q. The incentives of the innovator to delay are stronger than the incentives of the buyers to sign earlier. This basic intuition seems very general as long as the price in the second period is increasing with the number of potential buyers. Furthermore, if profits also depend on n, this creates a countervailing effect ($\pi(n)$ decreases and $-E[c_{n2}]$ increases), as in the previous sections. The total effect cannot be characterized without putting more structure on the profit function and on the distribution F, but this exercise could be easily conducted.

4.2 Milestone payments

We previously limited the analysis to contracts that involved a single upfront payment for the innovation. In practice, most licensing contracts are more sophisticated and employ milestone payments and/or royalties to mitigate adverse selection. The problem of asymmetric information can be entirely overcome if the contract involves only a milestone payment. In that case, the license is signed in the first period, the buyer develops the product and makes the final payment in the second period if the product is revealed to be good.

However, we never observe contracts with pure milestone payments in our data on licensing contracts. Milestone-only contracts may not be feasible in the presence of a liquidity-constrained innovator. As well, such contracts may lead to moral hazard for buyers, who may not have sufficient incentives to develop the product. A detailed examination of these factors is beyond the scope of this paper. If we introduce an explicit constraint on how large the upfront payment needs to be, the effect of market structure on the date of licensing is still relevant. More generally, whenever contracts terms cannot completely offset the asymmetry, our results are still relevant and inefficient delays may arise.

5 Empirical analysis

5.1 Background on the pharmaceutical industry

The results of our theoretical model are tested on data from the pharmaceutical industry. We provide in this section some background on this industry and explain in particular why the theoretical assumptions we made appear reasonable in this context. As mentioned in the

introduction, there is an increasing division of labor between biotechnology companies, which perform the early stage discovery and research, and large pharmaceutical companies, which do the clinical development and marketing. Typically, drugs are transferred by signing an exclusive license, but also through direct acquisition of the company by the large firm. We focus in our empirical analysis on the licensing channel.

Drug development is an expensive and lengthy process. It involves several distinct phases defined by regulatory agencies.[30] 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, as is assumed in our model.

Development and testing costs are very high in this industry and typically increase significantly with each phase.[31] There are reasons to believe that testing costs should be higher for biotech companies than for large pharmaceutical companies. Large pharmaceutical companies 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.

An essential element of the model is that the licensor is better informed about the prospects for the drug candidate than the potential licensees. This asymmetric information is critical for deviations from the socially optimal timing. The empirical literature attempting to assess the extent of adverse selection in this industry obtains mixed results.[32] Demonstrating adverse selection is an empirical challenge. For example, the existence of a positive correlation between licensing and failure is only evidence of adverse selection if it holds after conditioning for all observable information used to determine the price of a license. That is, licensed-in projects may be higher risk and therefore have higher failure rates, but if the risk is easy for the licensee to assess (no information asymmetry), the price of the license will reflect this. However, there is at least casual evidence that industry practitioners worry about it (see Mason et al. (2008)). 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. Note that some contractual terms and licensing procedures, such as milestone payments and due diligence, clearly target this problem. However, these solutions are costly and imperfect, and some asymmetries will remain.

[30] such as the Food and Drug Administration (FDA) in the United States or the European Medicines Agency (EMA).

[31] According to the Tufts Center for the Study of Drug Development, "[b]etween the time research begins to develop a new prescription medicine until it receives approval from the Food and Drug Administration (FDA) to market the drug in the United States, a drug company typically spends $802 million over the course of 10 to 15 years." This center also claims that out of every 5000 drug candidates, only 1 is ultimately approved for marketing.

[32] Pisano (1997) finds higher failure rates of drug candidates licensed in from biotechnology firms than those developed in-house by pharmaceutical firms, though Arora et al. (2004) find the opposite.

We emphasize that, as we pointed out in section 3.3, if our assumption of asymmetric information is incorrect but the other elements of our model are appropriate, we should not expect to find any effect of market structure on the timing of licensing. Our results can thus be seen as indirect evidence that such asymmetries do exist. In our empirical analysis (see section 6.3), we examine the effect of market structure in cases where the severity of asymmetric information may differ. Moreover, we also show in Allain et al. (2011) that market structure would have a similar effect on delay in a model with overconfidence, rather than information asymmetry. While we do not attempt to distinguish these explanations empirically, they can be considered as two separate contributions of this paper.

5.2 Data

We draw our sample of licensing contracts from Recombinant Capital's rDNA database.[33] It contains detailed information on all licensing deals in the pharmaceutical industry signed since 1973 (we have the data up to 2007), including financial details (total value, up-front 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.

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, produced by IMS Health. MIDAS provides us with annual data on total revenues by disease from 15 countries. The R&D Focus database tracks all drug candidates, or projects, in development since the early 1980s. From this source, we not only add additional information about the development status of each licensed product, but we can determine the experience (in developing drugs, as well as marketing approved products) in different anatomical therapeutic classes (ATCs), of both the licensor and licensee. This will allow us to build different definitions of potential buyers of a license as well as important control variables.

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. 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

[33] This database is typically licensed by major pharmaceutical companies or other firms for a large fee but is also made available for a lower rate for academic research.

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.

Important for our definitions of potential buyer and downstream market is a drug's Anatomical Therapeutic Chemical classification (hereafter therapeutic class).[34] 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 as substitutes, but drugs within the same narrow class are closer substitutes than those in the same broad class, and 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 therapeutic substitutes.

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 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 as of 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 6.4.

[34]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."

Table 1: Summary statistics

Variable	N	Mean	StdDev	Min	Max
Late signing (post-preclinical)	2066	0.287	0.452	0.0	1.0
Log(months since start of preclinical)	1814	1.120	1.816	0.0	5.594
Licensor market experience (no. drugs marketed)	2047	3.204	13.654	0.0	198.0
Licensor development experience (no. drugs in development)	2047	6.383	16.437	0.0	302.0
Licensor deal experience (no. deals previously signed)	2047	1.491	2.468	0.0	17.0
Licensor is publicly traded	2066	0.150	0.357	0.0	1.0
Licensor is based outside US	2066	0.424	0.494	0.0	1.0
Firms are co-located (same country of headquarters)	2066	0.424	0.494	0.0	1.0
Licensor is not in VentureXpert data	2047	0.488	0.500	0.0	1.0
Licensor's round of venture financing	1026	3.693	2.680	1.0	20.0
Licensor's funding in last round of venture financing	1026	10.901	18.653	0.0	150.0
Licensor's cumulative venture financing	1026	28.516	33.106	0.0	244.590
Licensor's age	1048	8.227	5.601	0.0	20.0
Total revenues in therapeutic class (millions of US$)	1672	4.273	4.772	0.000	30.563
Total venture funding for industry (units of US$)	2065	9.147	4.230	0.000	16.671
Potential buyers	2047	42.399	27.726	0.0	113.0
Incumbents that sign at least one license	2047	22.778	19.951	0.0	80.0
Entrants that sign at least one license	2047	19.620	15.059	0.0	94.0
Incumbents, all firm types	2047	63.512	59.092	0.0	243.0
Entrants, all firm types	2047	35.915	33.867	0.0	230.0
Incumbents that are large and public	2047	8.128	5.085	0.0	20.0
Entrants that are large and public	2047	7.671	5.350	0.0	24.0

5.3 Empirical specification

We want to test empirically our theoretical predictions on the link between market structure and the timing of licensing. We present two main categories of results. First we use our baseline model, which treats all potential buyers as symmetric. In this case, as described in section 3, the theoretical model predicts an inverted-U shape relationship between number of potential buyers and delay in licensing. We test this prediction using as main explanatory variables both the number of potential buyers and this number squared. Second, we use the model of section 3.2.3, which differentiates incumbents with stakes on the markets and potential entrants. The explanatory variables of interest in this case are the number of incumbents and the number of entrants.

For both sets of analysis we use the same empirical methods: logit, ordered logit and a hazard rate model. The first approach is to define an "early" stage of licensing, such as the discovery and preclinical phases, and a "late" stage as Phase I, II and III clinical trials. Because regulators are directly involved beginning in Phase I, we consider this stage to be the point at which information about quality is verifiable. As well, this is the point at which testing involves human subjects and more complicated study design. 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 2 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). In the case of the ordered logit, for example, the observed dependent variable takes a discrete value corresponding to the development stage at signing as follows:

$$\begin{aligned} y &= 0 \quad \text{(discovery phase) if } y^* \leq 0 \\ &= 1 \quad \text{(preclinical phase) if } 0 < y^* \leq \mu_1 \\ &= 2 \quad \text{(Phase I) if } \mu_1 < y^* \leq \mu_2 \\ &= 3 \quad \text{(Phase II) if } \mu_2 < y^* \leq \mu_3 \\ &= 4 \quad \text{(Phase III) if } \mu_3 \leq y^* \end{aligned}$$

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 is indeed revealed. Another approach, and that taken by Gans et al. (2008), is the

use of a hazard model. This approach treats a biotechnology firm's innovation as "at risk" for licensing 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. While this is our main focus, we include a number of controls that might also 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 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.

6 Results

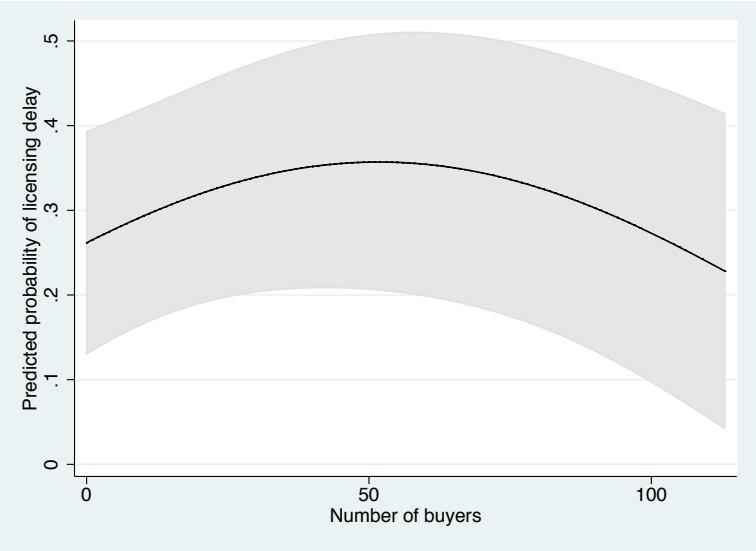
We test separately the predictions of our baseline model and those of the model differentiating entrants from incumbents. Most of our robustness checks, such as varying the definition of potential buyers, will be presented in this second case.

6.1 The inverted U-shape

Our starting point in this section is the condition for signing in the first period given in Proposition 2. We have shown that this condition is easier to meet when the number of competitors increases in an already very competitive market, but that this condition is less likely to hold in a very concentrated market. The theoretical model therefore predicts an inverted-U shape relationship between number of potential buyers and delay in licensing. We test this prediction by using the number of potential buyers and its square as the main explanatory variables. We expect a positive effect of the number of buyers and a negative effect of the squared term.

We define the set of potential licensees of an innovation as those with existing products in the same broad disease area, or 2-digit ATC, as the drug candidate licensed. Relative to firms in other disease areas, firms meeting this definition are likely to have a good understanding of the market potential and to be well-positioned to evaluate the scientific validity of a drug candidate available for license. In addition, such firms have pre-existing relationships with doctors who

Figure 6: Effect of competition on the probability of late signature



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. However, firms may use licensing as a means of entering a disease area, and some firms focus exclusively on internal development; indeed, any definition of potential licensee risks excluding some actual buyers and/or including some that are not true competitors for the license. 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. Robustness checks with respect to the definition of potential buyers are presented in section 6.4.

Table 2 presents our baseline results for the three econometric models described above. As predicted by our theoretical model, the number of potential buyers of a license has an inverted U-shaped effect on the timing on licensing. This effect is illustrated in Figure 6, which graphs the predicted probability of late signing (using the estimates of the logit model) as the number of buyers changes with continuous variables at their means for a US-based licensor that is not publicly traded. The mean number of buyers using our very inclusive definition is 42, and the peak of the inverted U is around 55.

Our main focus is on the effect of market structure on the timing of licensing, for which our model proposes clear and testable predictions. We do not want to insist too much on the interpretation of the coefficients on the other explanatory variables, though controlling for them could be important. The interpretation of the effect of being in the same location is unambiguous: it will tend to decrease asymmetric information, and thus, consistent with our theoretical model, lead to earlier licensing. But a lot of the other variables can reflect several competing effects. In general a high value of q (i.e high chance of having a successful drug) is often accompanied by a lower Δ (smaller efficiency difference with potential buyer). For instance, older firms or those that are publicly traded might have better products (higher q), but also be less liquidity constrained or have already access to cheaper ways of conducting

Table 2: Baseline results

Variable	Logit	M-Logit	Hazard
Intercept	-2.2233**	-1.6605**	-0.1384
	(0.5437)	(0.4523)	(0.4369)
Buyers	0.0161*	0.0140*	0.0240**
	(0.0097)	(0.0080)	(0.0080)
Buyers squared	-0.0002**	-0.0002**	-0.0002**
	(0.0000)	(0.0000)	(0.0001)
Total venture funding for industry	0.0225	0.0429**	0.0476**
	(0.0219)	(0.0184)	(0.0186)
Total revenues in therapeutic class	0.0363**	0.0327**	0.0161
	(0.0138)	(0.0119)	(0.0124)
Licensor market experience	0.0076	-0.0015	0.0115
	(0.0108)	(0.0096)	(0.0096)
Licensor development experience	-0.0047	0.0059	-0.0118
	(0.0107)	(0.0095)	(0.0095)
Licensor deal experience	-0.0193	-0.0471**	-0.0057
	(0.0235)	(0.0203)	(0.0205)
Licensor is publicly traded	0.5088**	0.4202**	0.6539**
	(0.1776)	(0.1537)	(0.1562)
Licensor is based outside US	0.0530	0.1234	-0.0053
	(0.1286)	(0.1086)	(0.1094)
Firms are co-located	-0.5903**	-0.4604**	-0.4542**
	(0.1282)	(0.1066)	(0.1050)
Licensor is not in VentureXpert data	0.4952**	0.5358**	0.4344**
	(0.2068)	(0.1730)	(0.1675)
Licensor's cumulative venture financing	0.0046	0.0053*	-0.0023
	(0.0035)	(0.0030)	(0.0032)
Licensor's funding in last round of venture financing	-0.0097	-0.0106**	0.0042
	(0.0059)	(0.0051)	(0.0050)
Licensor's round of venture financing	-0.0226	-0.0185	0.0306
	(0.0382)	(0.0331)	(0.0326)
Licensor's age	0.0711**	0.0712**	0.0792**
	(0.0157)	(0.0134)	(0.0139)
Number Obs	1633	1633	1449
Log L or R^2	-935.4465	-2084.579	.085

Table 3: Results with incumbents and entrants

Variable	Logit	M-logit	Hazard
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)
Number Obs	1633	1633	1449
Log L or R^2	-926.4657	-2069.873	.095

clinical trials (lower Δ). Our reduced-form empirical approach limits the interpretation of the coefficients on these measures.

6.2 Entrants and incumbents

In reality, 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 entrants. We estimate the model of section 3.2.3 that differentiates incumbents from entrants. We showed that the number of entrants unambiguously delays licensing. The effect of the number of incumbents could be potentially ambiguous, but we showed that in general we should expect an increase in the number of incumbents to speed up licensing. We therefore use, in the following specifications, as main explanatory variables the number of entrants and incumbents. We expect a negative effect of incumbents on delay and a positive effect of the number of entrants.

Using a similar logic to our definition of potential buyers discussed above, we now 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 3; 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.

6.3 Asymmetric information

In our model, inefficiencies arise only in the presence of asymmetric information. To confirm the importance of this factor, we test our model on different sub-samples for which we expect information asymmetries to be high or low. Asymmetric information is difficult to quantify,

Table 4: Results comparing 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

but we argue that it is 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.[35]

Table 4 indicates that our results are strongest for the subset of deals where asymmetric information is likely to be high (as above, 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 is not an underlying mechanism driving the timing of licensing.

6.4 Alternative definitions of potential buyers

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. Levine (2007), in her paper on licensing of biotechnology drugs, defines a potential buyer as any firm that markets a biotechnology product in the US, and allows their 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.

[35]Note that this split can also possibly separate firms according to their degree of over-confidence.

Table 5: Results with first alternative definition of potential buyers

Variable	Logit	M-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 6: Results with second alternative definition of potential buyers

Variable	Logit	M-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

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 5 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 6, 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.

7 Conclusion

In this paper we analyze, both theoretically and empirically, inefficiencies in the transfer of technologies. We focus in particular on a question that has been largely neglected in the literature, the effect of competition on the timing of technology transfers. One of the important conclusions is that a decrease in the number of incumbents and an increase in the number of entrants on the market may inefficiently delay the signature of a license contract, or more generally, that

competition has two countervailing effects on the efficiency of markets for technology.

We present a model of sequential bargaining that incorporates a number of elements that characterize markets for technology in practice. Of particular importance is the asymmetry of information between the buyer and seller of an idea. Despite the complexity that it shares with other models of sequential bargaining, we are able to obtain testable predictions that match the predictions of an auction model, and are confirmed by our empirical analysis of licensing in the pharmaceutical industry. Empirically, our results on the effect of competition on licensing of pharmaceuticals are economically significant: 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.

The ambiguous effect of competition on delays in licensing appears to be robust: the theoretical model is quite general and we obtain similar results with a bargaining model and with an auction model. Empirically, though the pharmaceutical industry provides a good illustration, our results should be relevant in any industry where the division of labour in the innovation process exists, early stage innovators have better information on the quality of their innovation than later developers, and information is revealed during the development of the invention.

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. However, 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.

Our paper also emphasizes the fact that boundaries of the firm change the terms of trade by affecting the degree of asymmetric information. A key tradeoff is highlighted: more integrated firm lower information asymmetries but at the expense of inefficiencies in production. In our application we focus on vertical integration within a research process but this general perspective could be more widely applicable.

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8 Appendix

Proposition 1

Consider the case where all negotiation 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 κ. As ϵ converges to zero, Binmore et. al. (1986) show that the bargaining outcome is defined by the Nash bargaining solution where the surplus is split equally. Under Assumption 1, $\pi - \pi_0 \geq \kappa$, and thus there is room for an agreement. The continuation equilibrium is thus such that a license is indeed sold to the last buyer at a price $p_2(1)$ defined by:

$$p_2(1) - \kappa = \pi - p_2(1) - \pi_0 \;\Rightarrow p_2(1) = \tfrac{1}{2}(\pi - \pi_0 + \kappa)$$

Consider now the previous negotiation rounds in the second period. When ϵ converges to zero we show the following recursive property:

$\mathbf{P_k}$: *When there are $k > 1$ buyers left in the sequence, a license is sold at a price $p_2(k)$, where:*

$$\mathbf{p_2(k)} = \left(\frac{\mathbf{1}}{\mathbf{2}}\right)^{\mathbf{k}} (\kappa + \pi_\mathbf{1} - \pi_\mathbf{0}) + \left(\mathbf{1} - \left(\frac{\mathbf{1}}{\mathbf{2}}\right)^{\mathbf{k}}\right)(\pi - \pi_\mathbf{1})$$

We first show this property for $k = 2$, i.e when there are only two buyers left in the sequence. Consider the negotiation between the innovator and the buyer before last ($k = 2$), assuming that all previous negotiations failed. Both firms anticipate that if they do not sign, bargaining with the last buyer will succeed: default options are thus π_l for the buyer and $p_2(1)$ for the innovator. If a license is signed, the price is determined by an equal split of the surplus and the recursive relation is therefore

$$p_2(2) - p_2(1) = \pi - p_2(2) - \pi_l$$

Using the value of $p_2(1)$ previously derived, we find:

$$p_2(2) = \left(\frac{1}{2}\right)(\kappa + \pi_l - \pi_0) + \left(\frac{1}{2}\right)(\pi - \pi_l)$$

The last step is to show that a license is indeed signed, i.e $\pi - \pi_l > p_2(1) \Leftrightarrow \pi - 2\pi_l + \pi_0 - \kappa > 0$. This condition is satisfied because of Assumption 1 and the fact that $\pi_0 > \pi_l$. Therefore, property P_2 is correct.

$\mathbf{P_{k-1}} \Rightarrow \mathbf{P_k}$: Consider the case where k buyers are left in the sequence. 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.[36] Therefore, an equal split of the surplus gives:

$$p_2(k) - p_2(k-1) = \pi - p_2(k) - \pi_l$$

According to P_{k-1}

$$p_2(k-1) = \left(\frac{1}{2}\right)^{k-1}(\kappa + \pi_l - \pi_0) + \left(1 - \left(\frac{1}{2}\right)^{k-1})(\pi - \pi_l\right)$$

Replacement in the previous expression gives:

$$p_2(k) = \left(\frac{1}{2}\right)^{k}(\kappa + \pi_l - \pi_0) + \left(1 - \left(\frac{1}{2}\right)^{k}\right)(\pi - \pi_l)$$

The last step is to show that a license is indeed signed, i.e there is room for bargaining: $\pi - \pi_l > p_2(k-1)$. This is equivalent to $\pi - 2\pi_l + \pi_0 - \kappa > 0$, property already shown to be correct. We have thus shown that P_k is correct.

The result stated in Proposition 1 is property $\mathbf{P_k}$ for $k = n$ buyers initially in the sequence.

Proposition 2

Note first that there cannot exist a separating equilibrium with signature in the first period, as a buyer would not pay a higher price for a license with a bad type, and if the price for the good type were higher a bad type innovator would always profitably deviate by mimicking a good type. We therefore focus on pooling equilibria. Note then that if $\Delta > p_2(n)$, 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 $\Delta \leq p_2(n)$. Note that the condition stated in Proposition 2 is $\Delta \geq \underline{\Delta}(n) = p_2(n) - q(\pi - \pi_l)$ where $\underline{\Delta}(n) < p_2(n)$ (see proof of Proposition 3). Thus if we show that the result of Proposition 2 holds for $\Delta \leq p_2(n)$ we have completed the proof.

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, and the price paid is $p_2(n)$.

Consider the last bargaining session in period 1. Consider a round where the buyer makes an offer. If he offers a price $p' > p_2(n) - \Delta$ this offer is accepted by both types of innovators. Indeed the best the innovator can hope for in equilibrium is to obtain $p_2(n)$ in the following period and he will have to pay Δ to develop the product from period 1 to period 2. With this offer, the utility of the buyer is $q\pi + (1-q)\pi_0 - p'$.[37] If he waits for period 2, his expected utility is $q\pi_l + (1-q)\pi_0$.

[36] Formally, the disagreement points are: $(1-\epsilon)p_2(k-1) + \epsilon(1-\epsilon)p_2(k-2) + ... + \epsilon(k-1)\kappa =$ for the innovator and $(1-\epsilon(k-1))\pi_l + \epsilon(k-1)\pi_0$. As ϵ converges to zero we obtain the reported disagreement points.

[37] Note that in a PBNE beliefs must be consistent on the equilibrium path so that the buyer expects the quality of innovation to be good with probability q.

The condition given in Proposition 2 guarantees that there exists a price p', acceptable to both types of innovators ($p' > p_2(n) - \Delta$) such that: $q\pi + (1-q)\pi_0 - p' > q\pi_l + (1-q)\pi_0$. 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'.

Consider first inside this session a round where the innovator makes the offer. For a good type innovation she always asks for a price $p_t \geq p_2(n) - \Delta$ as she knows she can guarantee herself at least $p_2(n) - \Delta$ by developing the product herself. The bad type will always mimic the behavior of a good type: if she reveals her type, no offer will be accepted or made to her. We examine the optimal response of the buyer. If the buyer accepts the offer, he obtains an expected payoff of $q'\pi + (1-q')\pi_0 - p_t$. However, he never accepts an offer that yields a smaller payoff than what he can guarantee himself if he rejects all offers and obtains his outside option $q'\pi_l + (1-q')\pi_0$. So, if $q'(\pi - \pi_l) < p_2(n) - \Delta$ no equilibrium offer by the innovator is acceptable to the buyer.

Consider now a round where the buyer makes an offer. In equilibrium he offers a price p_t that is such that $q'\pi - p_t \geq q'\pi_l$. Furthermore, he knows that all offers lower than $p_2(n) - \Delta$ will be rejected by the good type innovator and might be accepted by the low type. Such an offer is never made in equilibrium. So if $q'(\pi - \pi_l) < p_2(n) - \Delta$, no equilibrium offer by the buyer is acceptable to the innovator.

Finally, 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.

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 anticipate 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.

Existence of an equilibrium

We show here that under the condition of Proposition 2, there exists a pooling equilibrium where a license is signed in the first period and firms have passive beliefs.

Assume that:

$$p_2(n) - \Delta \leq q(\pi - \pi_l)$$

There exists an equilibrium where a license is signed with the first buyer to negotiate in the first period. The following strategies sustain this equilibrium:

- If negotiation starts with the $n-k+1_{th}$ potential buyer in the sequence, and if this buyer believes that the innovation is good with probability q':
  - In any round where the buyer makes the offer, it offers $p_1(k) \equiv q(\pi - \pi_l)(1 - \frac{1}{2^k}) + \frac{1}{2^k}(p_2(n) - \Delta)$;
  - In any round where the seller makes the offer, it offers $p_1(k)$;
  - In any round where the seller makes the offer, the buyer accepts the offer if and only if it is lower than or equal to $p_1(k)$;
  - In any round where the buyer makes the offer, the seller accepts the offer if and only if it is higher than or equal to $p_1(k)$.
- Initially, all potential buyers share the same prior belief regarding the quality of innovation (that it is good with probability q). We assume that out-of-equlibrium beliefs are passive (*i.e.* if a buyer receives an out-of-equilibrium offer, he does not modify its beliefs: see McAfee & Schwartz (1994).

Note that a bad innovator mimics the strategy of a good innovator. We show that there is no profitable deviation from this equilibrium candidate. If all negotiations fail in the first period, we have characterized in Proposition 1 the second period continuation equilibrium outcome. We consider now the first period.

There is no profitable deviation in this bargaining sequence:

- If the seller deviates by asking for a higher price $p_D \geq p_1(k)$ in a round where it makes the offer, with passive beliefs the buyer does not revise its beliefs. The buyer thus does not accept the offer.
- If the seller deviates by asking for a lower price $p_D \leq p_1(k)$ in a round where it makes the offer, with passive beliefs the buyer does not revise its beliefs. The buyer accepts the offer but this deviation is not profitable for the seller, irrespective of its type, as it can obtain $p_1(k)$ in the next round.
- If the buyer deviates by offering a higher price $p_D \geq p_1(k)$ in a round where it makes the offer, the seller accepts the offer and it is not profitable for the buyer.
- If the buyer deviates by offering a lower price $p_D \leq p_1(k)$ in a round where it makes the offer, the seller will not accept the offer.

Proposition 3

According to the result of Proposition 1, the price of a license in the second period is given by:

$$p_2(n) = (\pi - \pi_l) - \frac{1}{2^n}(\pi - 2\pi_l + \pi_0 - \kappa)$$

Furthermore, Assumption 1 and $\pi_l \leq \pi_0$ imply that $\pi - 2\pi_l + \pi_0 - \kappa > 0$. Thus, $p_2(n)$ increases with n.

We can reexpress the condition of Proposition 2 that guarantees that the license is signed in the first period:

$$\begin{aligned} \Delta &\geq \underline{\Delta}(n) \\ \text{where } \underline{\Delta}(n) &= p_2(n) - q(\pi - \pi_l) \end{aligned}$$

We have

$$\underline{\Delta}'(n) = [\pi - 2\pi_l + \pi_0 - \kappa]\ \frac{\ln(2)}{2^n}$$

Therefore $\underline{\Delta}(n)$ is increasing in n.

Proposition 4

In the case where profits depend on n, we find:

$$p_2'(n) = (\pi'(n) - \pi_l'(n)) + \frac{\ln(2)}{2^n}(\pi(n) - 2\pi_l(n) + \pi_0(n) - \kappa) - \frac{1}{2^n}(\pi'(n) - 2\pi_l'(n) + \pi_0'(n))$$

Furthermore, we examine how the benchmark $\underline{\Delta}(n)$ varies with n

$$\underline{\Delta}'(n) = p_2'(n) - q\left[\pi'(n) - \pi_l'(n)\right]$$

We see that if we take the limit as $n \to +\infty$

$$\lim_{n\to+\infty} \underline{\Delta}'(n) = \lim_{n\to+\infty} (1-q)\left(\pi'(n) - \pi_l'(n)\right)$$

Under the condition of Proposition 4, $\lim_{n\to+\infty} \underline{\Delta}'(n) \leq 0$ and thus the probability of signing in period 1 increases in n.

Bertrand competition with differentiated products

The consumer's utility is given by

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

where q_i is the quantity of good i consumed, μ is the degree of product substitution between the goods ($\mu \in [0, +\infty[$) and v is positive and larger than c.

The demand for each good is thus

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

If no license is signed, all n firms are symmetric, each selling one good. Profit maximization of the symmetric game yields the following prices and profits:

$$\begin{aligned} p_i &= c + \frac{n(v-c)}{2n+\mu(n-1)} \\ \pi_0(n) &= \frac{(v-c)^2(n+\mu(n-1))}{(2n+\mu(n-1))^2} \end{aligned}$$

Consider now the case where one firm, say n, signs a license with the innovator in possession of a good type innovation, thus introducing a new product. The competition game is now asymmetric, firm n selling two of the existing $(n+1)$ products, whereas its competitors sell one each.

Firm n's profit is now

$$\Pi_n(p_n, p_{n+1}) = (p_n - c)D_n(p_1, ...p_n, p_{n+1}) + (p_{n+1} - c)D_{n+1}(p_1, ...p_n, p_{n+1})$$

Whereas firm i's profit, for $i \in \{1, .., n-1\}$, is

$$\Pi_i(pi) = (p_i - c)D_i(p_1, ...p_n, p_{n+1})$$

The equilibrium of the pricing game yields the following prices (all prices are above c and generate positive demands):

$$\begin{aligned} p_i &= \frac{v + (1+\mu)(nv + c(1+n+(n-1)\mu))}{2 - \mu^2 + n(1+\mu)(2+\mu)} \text{for } i \in \{1, ..., n-1\} \\ p_n &= p_{n+1} = \frac{v(2+\mu+2n(1+\mu)) + c(2+2n(1+\mu)^2 - \mu(1+2\mu))}{4 - 2\mu^2 + 2n(1+\mu)(2+\mu)} \end{aligned}$$

and the profits are

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

We check that $\pi_l \leq \pi_0$.

Proposition 5

Claim: *In equilibrium the license is signed in period 1 iff the following conditions are satisfied:*

$$\Delta > \widehat{\Delta}(n, e) = p_2^{E,I}(e, n) - q\pi_e$$

where $p_2^{E,I}(e, n)$ is the price in the second period where the license is sold to the first entrant at a price:

$$p_2^{EI}(e, n) = (1 - \frac{1}{2^e})\pi_e + \left(\frac{1}{2}\right)^{n+e}(2\pi_l - \pi_0 - \pi) + \tfrac{1}{2^e}(\pi - \pi_l)$$

Proposition 5 is then a direct consequence. Indeed we have:[38]

$$\widehat{\Delta} = p_2^{E,I}(e,n) - q\pi_e = (1-q)\pi_e + \tfrac{1}{2^e}\left[\pi - \pi_l - \pi_e + \left(\frac{1}{2}\right)^n (2\pi_l - \pi_0 - \pi)\right]$$

We therefore have:

$$\frac{\partial\widehat{\Delta}}{\partial e} = -ln(2)\tfrac{1}{2^e}\left[\pi - \pi_l - \pi_e + \left(\frac{1}{2}\right)^n (2\pi_l - \pi_0 - \pi)\right] > 0$$

and

$$lim_{e\to+\infty}\frac{\partial\widehat{\Delta}}{\partial n} = (1-q)\frac{\partial\pi_e}{\partial n} < 0$$

Proof of the claim:

Second period The sequence of bargaining in both periods is e entrants followed by n incumbents. In period 2, if bargaining fails with the e entrants, under Assumption 1 a license will be signed with the first incumbent at a price $p_2^{EI}(0,n) = \left(\frac{1}{2}\right)^n(\pi_l - \pi_0) + \left(1 - (\frac{1}{2})^n\right)(\pi - \pi_l)$ (same reasoning as for equation (2) in Proposition 1).

Consider the second period negotiation with the last entrant. If bargaining fails, the innovator obtains $p_2^{EI}(0,n)$ and the entrant 0. If it succeeds, the innovator gets $p_2^{EI}(1,n)$ and the entrant $\pi_e - p_2^{EI}(1,n)$. The equal split of the surplus implies:

$$p_2^{EI}(1,n) = \frac{1}{2}(\pi^e + p_2^{EI}(0,n)) = \frac{1}{2}\pi^e + \left(\frac{1}{2}\right)^{n+1}(2\pi_l - \pi_0 - \pi) + \tfrac{1}{2}(\pi - \pi_l)$$

If it starts, negotiation with the last entrant succeeds since $\pi_e > \pi > p_2^{EI}(0,n)$ implies $p_2^{EI}(1,n) > p_2^{EI}(0,n)$. Note that $p_2^{EI}(1,n) < \pi_e$.

Consider the second period negotiation with the entrant before last. If bargaining fails, the innovator obtains $p_2^{EI}(1,n)$ and the entrant 0. If it succeeds, the innovator gets $p_2^{EI}(2,n)$ and the entrant $\pi_e - p_2^{EI}(2,n)$. The equal split of the surplus implies:

$$p_2^{EI}(2,n) = \frac{1}{2}(\pi^e + p_2^{EI}(1,n)) = (1 - \frac{1}{2^2})\pi^e + \left(\frac{1}{2}\right)^{n+2}(2\pi_l - \pi_0 - \pi) + \tfrac{1}{2^2}(\pi - \pi_l)$$

Note that $p_2^{EI}(2,n) > p_2^{EI}(1,n)$. As a consequence, under Assumption 1, if negotiations start in the second period, signature occurs with the first entrant at a price

$$p_2^{EI}(e,n) = (1 - \frac{1}{2^e})\pi^e + \left(\frac{1}{2}\right)^{n+e}(2\pi_l - \pi_0 - \pi) + \tfrac{1}{2^e}(\pi - \pi_l)$$

First period

[38] Since $\pi^e > \pi$ and by Assumption 1, $2\pi_l < \pi_0 + \pi$

We now show that a license is signed in period 1 if and only if:

$$\Delta > \widehat{\Delta}(n,e) = p_2^{E,I}(e,n) - q\pi_e \tag{5}$$

First step: suppose condition (5) is satisfied and a license is signed in period 2.

We show that then, in any PBNE, there exists a deviation in the first period. Consider negotiation with the last entrant in period 1. If the negotiation fails, this entrant knows he will not sign a license and will make zero profits.[39] If he signs he expects a profit π_e: in a round where he makes an offer, he can offer a price larger than $p_2^{E,I} - \Delta$ and get a larger surplus than by waiting if condition (5) is satisfied; Such an offer will be accepted by both types of innovators, and this constitutes a deviation from the candidate equilibrium.

Second step: Suppose condition (5) is not satisfied. Then we show a license is signed in the second period.

Following the same logic as Proposition 2, we know that in this case, if $p_2^{E,I}(e,n) - \Delta > q(\pi - \pi_{le})$, no profitable deviation is possible in negotiation with the last incumbent in period 1. This condition is implied by the fact (5) is not satisfied since $\pi_e > \pi$. The same logic applies for all the previous incumbents who effectively become the last.

Given condition (5) we also know that none of the entrants other than the first will sign in period 1 either. Consider finally the negotiation with the first entrant in the sequence. If he signs in period 1, his expected reward is $q\pi_e$ while if he waits, his expected profit is $q(\pi_e - p_2(0,e))$. So if $q\pi_e - q(\pi_e - p_2(0,e)) < p_2(0,e) - \Delta$. Since $p_2(0,e) \leq \pi_e$, this condition is implied by by the fact (5) is not satisfied. We have shown that therefore there is no deviation in the first period.

Proposition 6

The proof is similar to the proof of Proposition 2 except that the buyer has no private information in the first period and believes his innovation is good with probability q. The condition for signing in period 1 thus becomes

$$q(\pi - \pi_l) \geq qp_2(n) - \Delta$$

This is equivalent to

$$\Delta \geq \underline{\Delta}(n) = q(\pi_l - \pi + p_2(n))$$

In Proposition 1 we established that $p_2(n) < \pi - \pi_l$ and thus $\underline{\Delta}(n) < 0$ for all values of q and n.

Proposition 7

Second period

In the second period, the type of the inventor is known. The reservation price fixed by the innovator is κ, her outside option. The unique equilibrium is such that all buyers bid exactly

[39] Since the order is identical in the second period

their valuation (equilibrium bidding strategy in a second price auction). Thus in the second period

$$p_2(n) = \pi(n) - c_{n2} \tag{6}$$

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

First period

In the first period, the equilibrium is defined by:

- Bidding strategies for the buyers
- Reservation price r chosen by the good type innovator (bad type innovator always sets zero reservation price in first period)

For a given reservation price r, we show that the unique equilibrium is such that a player with cost c bids his valuation $q[\pi - c]$ if it is above r and bids zero if it is below.

If $q[\pi - c] < r$, in equilibrium, the buyer bids zero. Indeed, any bid above $q[\pi - c]$ would give a loss in expectation and any bid below is accepted only by the low type innovator since $q[\pi - c] < r$. In what follows we show that in the case where $q[\pi - c] > r$, the unique equilibrium strategy is to bid the valuation $q[\pi - c]$.

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

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

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

Case 3 bid b is not the highest bid and highest bid, denoted b_1, is below the reservation price (which means $b_1 \leq q[\pi - c]$). The profits if the buyer bids $q[\pi - c]$ are $q[\pi - c] - b_1 \geq 0$.[40] If $\pi - c$ is not the highest valuation among the n bidders, then the bidder would lose the auction in period 2 and strictly prefers bidding $q[\pi - c]$ this period. If he has the highest valuation, we denote $\pi - c_{n2}$ the second highest valuation. In the second period, if the innovation is good he will win the auction and make profits $\pi - c - (\pi - c_{n2})$. So, if he does not deviate, his expected profits are $q(c_{n2} - c)$. If he deviates and bids $q[\pi - c]$, his profits are $q[\pi - c] - b_1$. Since for a player with cost c, we eliminated the dominated strategy of bidding strictly more than $q[\pi - c]$,

[40] We assume that as long as the highest bid is above the reservation price, the sale occurs at the second highest bid, even if it is lower than the reservation price: assuming that the price paid is the reservation price would not qualitatively change our results.

we know that $b_1 \leq q[\pi - c_{n2}]$. So when he bids $q[\pi - c]$ the bidder expects profits greater than $q[\pi - c] - b_1 \geq q[\pi - c] - q[\pi - c_{n2}] > q[c - c_{n2}]$.

We have therefore shown by elimination of weakly dominated strategies, that, for any reservation price r, the unique equilibrium is such that a player with cost c bids his valuation $q[\pi - c]$ if it is above r and bids zero if it is below.

We now show that if she runs an auction in the first period, the innovator chooses a zero reservation price. If the second highest bid is below the reservation price, the auction is run again in the next period. We note however that the incentives to wait are higher when the valuations are higher. Indeed, given the strategies of the bidders in the first and second periods, if the second highest bid is b in the first period, then the second highest bid would be b/q in the second (since in the first the players bid their valuation times the probability the type is good). So the innovator should accept the first period bid if:

$$b \geq \frac{b}{q} - \Delta \Leftrightarrow b \leq \frac{q}{1-q}\Delta$$

The incentives to wait are higher for higher valuations, so no reservation price is placed (for low values the innovator wants to sell now).

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

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

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.