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Designing Auctions in R&D: Optimal Licensing of an Innovation

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Abstract

We study an R&D game in which a research unit undertakes a (non-observable) research effort and, if an innovation is obtained, auctions licenses to a pool of producers. Each producer has a private valuation for the license and suffers a negative externality when a competitor becomes a licensee. We compare the optimal rule for the allocation of licenses and the level of research effort implemented by the innovator in two scenarios: free licensing by the innovator vs. optimal regulation. As long as the cost of public intervention is sufficiently low, free licensing induces two different types of inefficiencies: an excessively high price for licenses and a suboptimal dissemination of knowledge, and an excessively low research effort. This indicates that public intervention should combine the following measures: (i) an antitrust agency which limits the royalties that innovators can ask for a license, and (ii) a direct subsidy to research activity.

KEYWORDS: R&D, auctions, externalities, licenses

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1 Introduction

Obtaining and disseminating innovations are key elements of economic performance. Since the introduction of new products and the improvement of existing technologies rely on research and development activities (R&D), public authorities have developed a series of tools that provide incentives to private agents to embark on costly R&D. Such intervention has two different (and often conflicting) goals: optimize the research effort exerted by innovators and maximize the dissemination of discoveries. One possible mechanism is to assign innovators property rights on their discoveries, with a system of patents and licensing. However, it has been widely argued that the protection of intellectual property may be an obstacle both to the dissemination of knowledge[1] and to the implementation of optimal research efforts.

Interestingly, the problems associated with the licensing of innovations have received much less attention than those associated to patent protection even though, in markets where licensing is feasible, the revenues generated with this mechanism constitute a substantial component of the incentives to engage in R&D.[2] As pointed in the literature, the main issue with licensing is that the innovator does not internalize the effects of his decisions on the other agents in the economy, and therefore his incentives to exert a research effort can be smaller or higher than the social ones.[3] However, to our knowledge, there is no theoretical analysis that studies jointly the problems of ex-ante optimal research effort and ex-post maximal dissemination of knowledge, despite their obvious relation.

The purpose of this paper is to fill this gap. We first investigate what are the social inefficiencies or distortions when an innovator freely selects both his research effort and the rule for selling licenses to producers. Then, we determine which kind of policies should a government agency implement in order to mitigate these inefficiencies. In our analysis, we concentrate on the two aspects that we consider key in this industry: (i) non-exclusivity of licenses that imply the existence of negative externalities between the firms competing

[1]For example, when technology improves rapidly and patents becomes quickly obsolete, innovators may decide to keep their innovation secret. They may also register several innovations, only one of them being the key of the new technology, in order to put competitors on the wrong track. Last, firms may prefer to exploit their monopoly power instead of sharing their knowledge (through licensing agreements) with others. See Crampes (1986), Mansfield (1992) and David (1995).

[2]Degnan (1999) reports that receipts from licensing agreements provide a substantial source of income for US private and public innovative firms.

[3]See e.g. Dasgupta and Stiglitz (1980), Lee and Wilde (1980), Katz and Shapiro (1985, 1986) for theoretical analyses and Reinganum (1989) for a survey.

in the product market, and (ii) existence of informational problems (moral hazard and asymmetric information) between the innovator, the producers and the government agency. Before developing our main conclusions, we would like first to discuss briefly these two elements.

A license is a product with two specific characteristics. First, non-exclusivity: in principle, the innovator can offer for sale as many licenses of his innovation as he wishes. Second, interdependence of valuations and negative externalities: as a result of non-exclusivity, the welfare of each producer depends positively on the likelihood of obtaining a license and negatively on the number of competitors who also do. Naturally, if the negative externality between producers is high, the innovator can extract more rents, as producers are willing to increase their payment not only to get the license but also to prevent others from obtaining it. The seminal contributions by Katz and Shapiro (1986) and Kamien and Tauman (1986) already noted that, under these circumstances, the nature of competition and therefore the equilibrium price mechanism is modified.[4] Overall, in the presence of negative externalities, the innovator will extract payments from producers for not selling licenses. As a result, the dissemination of knowledge will tend to be suboptimal from a social viewpoint, which calls for the necessity of intervention.

The second element, namely the existence of informational problems, is also key for our analysis. On the one hand, each firm has an intrinsic ability or capacity to exploit the license, which determines his privately known willingness to pay for it. On the other hand, the research effort of the innovator is not observable, so even if a social planner intervenes at the research stage, she can neither monitor nor force the research laboratory to exert a specific amount of effort.[5] These asymmetric information and moral hazard issues affect the relationship social planner-innovator-producers in a number

[4]Also, Kamien, Oren and Tauman (1992) argue that when producers face Cournot competition on the product market, then the seller can extract rents from firms that do not get the license. In a different setting, Scotchmer (1996) states that the patent-holder of a first generation innovation who licenses its use to develop a second generation invention can extract more profits than the reservation payoffs of licensees. This occurs because the licensees will enter the race for the second generation invention. Last, the auction literature with negative externalities (see e.g. Jehiel et al. (1996) and (1999)) shows that, in the optimal auction mechanism, some of the purchasers pay an entry fee, yet do not receive the good. Moreover, the reserve price is distorted upwards with respect to the standard optimal one.

[5]One can think of other possible asymmetries. The research laboratory may have better knowledge about the quality of his innovation than the producers. Also, the externality suffered when a competitor gets the license may depend on the firm's value. While the first asymmetry could be easily introduced in our model, the second one would somewhat modify the analysis. In any case, these and other possible extensions are discussed in the paper.

of ways. Most previous analyses related to R&D incentive schemes have neglected them. Moreover, our claim is that the ex-ante moral hazard problem in the innovator's choice of effort and the ex-post asymmetric information issue in the allocation of licenses need to be treated jointly.

Combining these two elements, the paper compares two situations. In the first one, the innovator has full control of his research effort and the pricing mechanism to sell licenses (the decentralized, non-regulated or free licensing case). In the second one, a public agency that maximizes industry or social welfare offers an incentive contract to the innovator to encourage his research activity and specifies the pricing mechanism for the sale of licenses. However, the revenue raised with licenses still goes directly to the innovator (the centralized or regulated case). For simplicity, we restrict ourselves to the situation in which each firm buys at most one license and neither the innovator or the regulator can produce.

As a first step, we determine the optimal dissemination of knowledge (that is, the mechanism for the allocation of licenses) under free licensing and under regulation. In both cases, the optimal mechanism is such that: (i) there are as many licenses for sale as producers in the market, (ii) the auctioneer extracts rents from non-acquirers via an entry fee, and (iii) the minimum price paid for a license is increasing in the size of the negative externality and the number of producers (Propositions 1 and 2). Intuitively, each producer is ready to pay not only to obtain the license but also to prevent others from acquiring it. This generates rents that can be captured by the seller. In particular, producers are ready to pay an entry fee to participate in the auction, as long as bidding diminishes the competitors' probability of obtaining the license. So, in the optimal mechanism, the seller threats producers who do not pay a participation fee to give the license to all those who participate, and sells licenses only to the firms with highest bids when everybody participates. Note that, since the presence of externalities generates rents in the economy, it is optimal even from the regulator's viewpoint to design an auction mechanism in which the innovator reaps some of these rents. However, given that the agency internalizes the social value of the innovation, we show that she always specifies a softer rule for the allocation of licenses (that is, a lower minimum price) than optimal from the innovator's perspective. This, in turn, increases the dissemination of the innovation and diminishes anticompetitive risks.[6] More-

[6]Katz and Shapiro (1986) reach a similar conclusion with respect to the number of licenses offered for sale in a complete information setting. They show that the innovator restricts the number of licenses offered (compared to the socially optimal level) when the gain of each producer increases in the willingness of competitors to get the license (agglomeration effect). Moreover, if the innovation is such that it creates a natural oligopoly of size k, then the

over, a regulatory agency will neither finance research nor promote licensing if the externalities generated in the industry are excessively high. This explains why antitrust authorities, both in the US and in Europe, closely monitor the licensing agreements. Indeed, as the model points, without a strict description of the conditions under which innovations can be licensed, the innovator would over-price his discovery (relative to the socially optimum) and therefore generate anticompetitive situations in the product market. Note however that increasing ex-post dissemination comes at the expense of decreasing the revenues of the auction, which itself affects the innovator's willingness to exert a research effort. This leads directly to the next conclusion.

In a second step, we address the issue of effort provision under free licensing and under regulation. Not surprisingly, under free licensing the innovator undertakes too little effort relative to the first-best optimum (i.e. relative to the case in which the regulator intervenes and can monitor effort, see Lemma 1) as he does not integrate the social value of the innovation. The optimal second-best effort under regulation and incomplete information crucially depends on the shadow cost of transferring public funds or, equivalently, the distortions of taxation. If this cost is sufficiently low, the regulator finds it optimal to subsidize with a transfer the research activity of the innovator which more than compensates him for his ex-post lower gains in the auction of licenses. This way, the innovator has incentives to exert a research effort close to first-best, so higher than under free licensing. The intervention of the regulatory agency is globally beneficial for welfare. However, it generates a budget deficit, since the revenues from the sale of licenses do not constitute a sufficient reward for the innovator. As the cost of public funds increases, the regulator optimally substitutes the costly financing (transfers raised through public funds) with the costless one (revenue of the auction). In other words, the subsidy is diminished and the optimal auction mechanism becomes closer to the revenue maximizing one. Naturally, this comes at the expense of a decrease in the dissemination of knowledge. Last, when the cost is sufficiently high, it becomes optimal to tax the innovator for his research activity. In this situation, the innovator ends up exerting less effort than in the free licensing case (Proposition 3, 4 and 5). Overall, it is interesting to notice that optimal regulation always implies higher ex-post dissemination of knowledge than free licensing. However, if subsidizing the research activity is sufficiently costly, then the ex-ante probability of innovating under regulation will be smaller than under free licensing (Proposition 6).

innovator will never offer more than k licenses. See also Gallini and Winter (1985), Gallini (1984), Katz and Shapiro (1985) and Kamien and Tauman (1986) for related analyses.

From a practical perspective, our model suggests that, in order to be effective, intervention in the R&D activity must combine three factors. First, antitrust authorities must supervise the allocation of licenses to avoid an excessively restrictive dissemination of knowledge. Second, the fiscal regime must be improved to ensure that the costs of transferring public funds are reasonably small. Third, the research activity must be subsidized with public expenditures in order to compensate innovators from their loss in the sale of licenses.[7]

The plan of the paper is the following. Section 2 presents the model, including the timing and the optimal auction mechanism for selling licenses. Section 3 characterizes the decisions of the innovator in the benchmark case of free licensing. Section 4 analyzes the optimal regulatory policy and compares research effort and dissemination under regulation and free licensing. Section 5 discusses some policy prescriptions in the light of our results. In particular, it analyzes the welfare properties of regulation and the effects of antitrust policies. Section 6 concludes.

2 The model

We consider an industry with one research laboratory or innovator and N producers. The laboratory undertakes a research and development activity in order to obtain an innovation. If the innovation succeeds, he sells licenses to the producers. Each producer purchases at most one license. For simplicity, we assume that the laboratory is not able to produce, so his revenue comes only from the sale of property rights. All parties are risk-neutral.

2.1 Payoffs and timing

The precise game we are going to consider has the following three stages.

<u>In the first stage</u>, the innovator chooses a non-observable research effort e that affects the probability of obtaining an innovation. More specifically, with probability $1-\pi(e)$, the research activity fails, the laboratory obtains no innovation and the game ends. With probability $\pi(e)$, the research activity succeeds, and an innovation is obtained by the laboratory. The quality of the

[7]Maurer and Scotchmer (2004) also analyzes the relationship between Antitrust Law and Patent Law and discusses the patent license restrictions that should be acceptable or not from an antitrust point of view. Our analysis offers a different but complementary approach. See also Gallini and Scotchmer (2002) and Menell and Scotchmer (2005) for related analyses of the merits of patent protection.

innovation is fixed and publicly observed. Effort is costly. We denote by $\psi(e)$ the disutility incurred by the laboratory when he exerts effort e. The probability of innovating and the disutility of effort satisfy the following assumption.

Assumption 1 (i) *$\pi'(e) > 0$, $\pi''(e) < 0$ and $\pi'''(e) \leq 0$ for all e.*
(ii) *$\psi'(e) > 0$, $\psi''(e) > 0$ and $\psi'''(e) \geq 0$ for all e. Moreover, $\psi(0) = 0$ and $\psi'(0) = 0$.*[8]

In the second stage, and if the innovation has been successful, the laboratory designs an auction in order to allocate licenses of the innovation among the producers. The procedure consists of a selection rule for the winner (or winners), a system of transfers paid by the participants and the number of licenses for sale. Each producer has a different ability to exploit the innovation. We denote by $v_i \in [\underline{v}, \overline{v}]$ producer i's "valuation" or willingness to pay for the license. It corresponds to the difference between his profits when he is the only one to obtain the license and his profits before the innovation took place.[9] We assume that valuations v_i are independently drawn from a common knowledge distribution with density $f(v_i)$ and cumulative distribution function $F(v_i)$ (see Remark 1 below for the implications of the independence assumption). The function $F(\cdot)$ is strictly increasing, continuously differentiable and satisfies $F(\underline{v}) = 0$ and $F(\overline{v}) = 1$. Last, as usual in auction theory, we assume that $F(\cdot)$ satisfies the monotone hazard rate property.

Assumption 2 $v - \dfrac{1 - F(v)}{f(v)}$ *is increasing in v.*

Each producer observes the mechanism proposed by the auctioneer and decides whether to participate or not. Denote by n $(\in \{1, ..., N\})$ the number of producers who decide to participate in the auction. Once the number of participants has been publicly observed, producers bid simultaneously. Winners are selected and payments are made according to mechanism A.

In the third stage, producers compete on the product market. Firm i suffers a negative externality $-\alpha_{ij}$ (with $\alpha_{ij} > 0$) when firm $j \neq i$ exploits the license. Concretely, α_{ij} represents the difference between the profits of producer i before the sale of licenses and his profits when j is the only producer to get the license. For simplicity, we assume that externalities are common

[8]The assumptions on the third derivatives are only sufficient conditions to ensure the overall concavity of the maximization program.

[9]The analysis can be extended to the case in which the quality of the innovation is neither observable nor fixed and known ex-ante. In that case, valuations would be a function of the quality (which could be disclosed at the time of the registration of the patent).

knowledge and symmetric (see also Remark 1 below for a discussion of the symmetry assumption). This is summarized as follows.

Assumption 3 $\alpha_{ij} = \alpha$ *for all* $j \neq i$.

For the time being, we neglect the possible externalities induced on consumers to isolate the effect of negative externalities between producers on pricing, effort and dissemination. We will relax this assumption in subsection 4.3.

To sum up, the overall timing of this three-stage game can be summarized as follows:

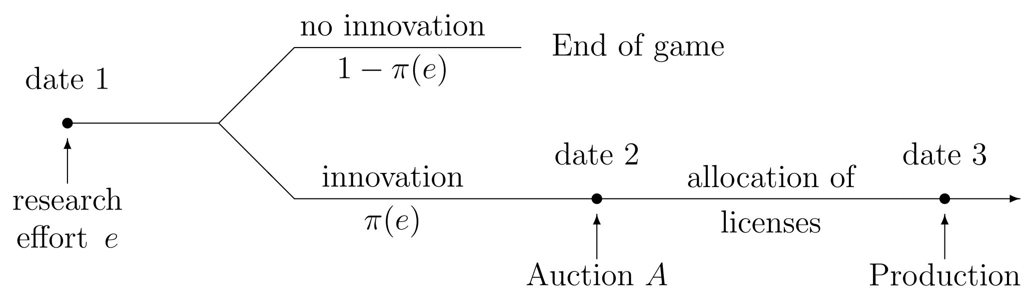

Figure 1. Timing

Remark 1. We have made two important simplifying assumptions, independence of valuations and symmetry of externalities, that need to be discussed jointly. Since, producers compete before the introduction of the innovation, each firm derives a profit in the status quo situation. Licensing of the innovation changes the structure of profits derived by producers. Formally, denote by π_i the profit of producer i in the status quo case, π_i^i $(> \pi_i)$ his profit if he is the only one to acquire the license and π_i^j $(< \pi_i)$ his profit if firm j is the only one to acquire it. Suppose also for simplicity that only one license can be sold. It then comes immediately that $v_i \equiv \pi_i^i - \pi_i$ and $\alpha_{ij} \equiv \pi_i - \pi_i^j$. One can immediately notice that, in general, valuations are not necessarily independent and externalities are not necessarily symmetric.[10] Recent theoretical papers analyze auctions with externalities when either valuations exhibit private and common value components (see e.g. Bulow et al, 1999) or externalities are asymmetric and privately known (see e.g. Brocas, 2005). Including these extensions does not usually modify the qualitative properties of the auction

[10]For instance, in a general Cournot competition game where the innovation decreases the cost of production we would have neither independence of valuations nor symmetry of externalities.

mechanism but it makes the technical analysis substantially more complex. Since we are more interested in the qualitative comparison of the optimal licensing mechanisms under free licensing and regulation than in the technical properties of the optimal auction, we think that independence and symmetry are reasonable assumptions.

Remark 2. Note that the innovator can sell several licenses. Given our simple framework, if v_i represents i's valuation when he gets the license alone and α the externality suffered each time that a competitor gets the license, then firm i's willingness to pay when he knows for sure that k other producers will also get the license is $v_i - k\alpha$. The assumptions relative to independence of valuations and symmetry of externalities help us to work with simple expressions of willingness to pay. Again, the analysis would not be qualitatively modified if we relaxed these assumptions. All we need is that each firm's modified valuation *decreases* as the number competitors who possess a license increases.

As we shall see in sections 3 and 4, the very presence of negative externalities impairs the efficiency of R&D policies in two respects. First, the innovator will extract rents from producers for limiting the number of licenses sold. As a result, the price of licenses will be inefficiently high and the number of producers who use the innovation inefficiently small. This implies that the intellectual property right (that allows innovators to charge high royalties) may be in conflict with the regulator's willingness to disseminate knowledge. Second, as a consequence of not internalizing the social value of his innovation, the innovator may choose an effort socially suboptimal at the research stage. In order to measure the effects of externalities, to analyze the efficiency of licensing as an incentive scheme, and to highlight some policy tools that could be of some help to improve welfare, we compare the following two situations. In the first case (section 3, decentralized licensing), the innovator chooses his intensity of research and designs the auction mechanism to allocate licenses. In the second case (section 4, regulation), a benevolent regulator offers a research contract to the innovator and fixes the auction mechanism for the sale of licenses. However, before proceeding to the comparison between these two situations, we will present the general properties of the auction mechanism proposed to the producers in stage two.

2.2 The auction mechanism

We assume that the designer of the auction or seller (the innovator in the decentralized case, the government agency in the regulated case) can commit to any mechanism A once he has proposed it to the producers. The ability to commit allows the seller to extract the maximum rents from the producers. In particular, by threatening each producer to give the licence for free to all the other producers if he does not participate in the auction, the auctioneer is (i) pushing each producer to his worst outside option (which corresponds to the case where all the other producers get the licence) and (ii) ensuring that all producers participate, which makes this an out-of-equilibrium threat. Although standard, this assumption is strong and will be discussed later on. As a result of commitment, we can concentrate on the auction with N bidders. Since the innovator and the regulator are not able to produce, we will assume without loss of generality that their valuation for keeping the innovation is zero.

The auction mechanism consists of an N-dimensional message space denoted by $\{M_1, \dots, M_N\}$ for the N producers participating in the auction (or bidders), a N-uple of winning probabilities and payments to the auctioneer (or seller) $\{x_i(\cdot), t_i(\cdot)\}$ as well as the number of licenses for sale k ($\in \{1, \dots, N\}$). Producers bid simultaneously by announcing their willingness to pay for the license $(\tilde{m}_1, \dots, \tilde{m}_N) = \tilde{m}$. The revenue of the seller is then:

$$\sum_{i=1}^{N} t_i(\tilde{m})$$

and the utility of producer i is:

$$v_i\, x_i(\tilde{m}) - \alpha \sum_{j \neq i} x_j(\tilde{m}) - t_i(\tilde{m})$$

The revelation principle implies that any Bayesian equilibrium $(\tilde{m}_1^\star(\cdot), \dots, \tilde{m}_N^\star(\cdot))$ for an auction consisting of $\{M_1, \dots, M_N, x_i(\cdot), t_i(\cdot)\}$ can be obtained as a Bayesian equilibrium for a direct mechanism that induces truthtelling. A direct mechanism is characterized by the interim probability that agent i gets the license:

$$X_i(v) = x_i(\tilde{m}_1^\star(v_1), ..., \tilde{m}_N^\star(v_N))$$

Let $\Phi(v_i, \tilde{v}_i)$ be the expected utility of firm i when his valuation is v_i, he announces $\tilde{v}_i$, and all the other bidders disclose their true valuations:

$$\Phi(v_i, \tilde{v}_i) = E_{v_{-i}}\Big[v_i\, X_i(\tilde{v}_i, v_{-i}) - \alpha \sum_{j \neq i} X_j(\tilde{v}_i, v_{-i}) - t_i(\tilde{v}_i, v_{-i})\Big] \qquad (1)$$

Let also $u_i(v_i) = \Phi(v_i, v_i)$ be the utility of firm i when he reports honestly. To be feasible, this direct mechanism must satisfy three kinds of constraints.

First, the mechanism must be *incentive-compatible*, i.e. producer i cannot be better-off by claiming that his type is $\tilde{v}_i$ ($\neq v_i$). Formally, $\Phi(v_i, v_i) \geq \Phi(v_i, \tilde{v}_i)$. It is standard to translate this constraint into the following first-order and local second-order conditions:[11]

$$\frac{d}{dv_i}\, u_i(v_i) = E_{v_{-i}} X_i(v) \tag{IC$_1$}$$

$$\frac{d}{dv_i}\, E_{v_{-i}} X_i(v) \geq 0 \tag{IC$_2$}$$

where, using (1), the equilibrium utility of firm i is:

$$u_i(v_i) = E_{v_{-i}}\Big[v_i\, X_i(v_i, v_{-i}) - \alpha \sum_{j \neq i} X_j(v_i, v_{-i}) - t_i(v_i, v_{-i})\Big] \tag{2}$$

Second, the seller cannot force the firms to participate in the auction. Given the previously mentioned commitment ability of the auctioneer, the *participation constraint* of firm i is:

$$u_i(v_i) \geq -\alpha(N-1) \tag{IR$_\text{i}$}$$

where $-\alpha(N-1)$ is the negative externality suffered by producer i when he does not participate and all the $N-1$ other producers get the license.

Third, the probability of allocating the license to each producer i in the optimal mechanism should also satisfy the following *feasibility* conditions:

$$X_i(v) \geq 0 \quad \forall\, i \tag{F$_0$}$$

$$X_i(v) \leq 1 \quad \forall\, i \tag{F$_1$}$$

We are now in a position to determine the optimal licensing mechanism offered by the innovator (section 3) and the regulator (section 4) to the producers at stage 2 of the game depicted in Figure 1.

[11] See Myerson (1981) and Laffont and Tirole (1993) Chapter 7 for more details on optimal auction design.

3 The decentralized (free-licensing) industry

Integrating (IC_1) we get:

$$u_i(v_i) = \int_{\underline{v}}^{v_i} E_{v_{-i}} X_i(s, v_{-i}) ds + u_i(\underline{v}) \tag{3}$$

Let R be the expected revenue of the seller-innovator, that is the sum of the transfers t_i obtained from the bidders. From equations (2) and (3) and with the help of the standard integration by parts technique employed in mechanism design problems (see e.g. Guesnerie and Laffont, 1984), we deduce that the expected revenue of the innovator can be written as:

$$R = \int_{\underline{v}}^{\overline{v}} \sum_{i=1}^{N} X_i(v) \left[v_i - \alpha(N-1) - \frac{1 - F(v_i)}{f(v_i)} \right] f(v)dv - N\, u_i(\underline{v}) \tag{4}$$

where $\int_{\underline{v}}^{\overline{v}} = \int_{v_1=\underline{v}}^{\overline{v}} \ldots \int_{v_N=\underline{v}}^{\overline{v}}$, $f(v) = f(v_1) \ldots f(v_N)$ and $dv = dv_1 \ldots dv_N$. The innovator's optimization problem consists of maximizing his expected revenue R under the incentive compatibility (IC_1)-(IC_2), individual rationality (IR_i) and feasibility (F_0)-(F_1) constraints. Our first result is a characterization of the optimal mechanism.

Proposition 1 *The optimal licensing mechanism from the innovator's point of view entails:*[12]
(i) *If $n = N$, the mechanism is direct, $k^I = N$ licenses are offered for sale and allocated according to the following selection rule:*

$$X_i^I(v) = \begin{cases} 1 & if \quad v_i \geq r^I \\ 0 & otherwise \end{cases}$$

where r^I solves: $\begin{cases} r^I - \alpha(N-1) - \frac{1-F(r^I)}{f(r^I)} = 0 & if \quad \alpha(N-1) < \overline{v} \\ r^I = \overline{v} & otherwise \end{cases}$

(ii) *If $n < N$, each participant receives one license for free.*

Proof: *See APPENDIX A1.*

This result deserves some comments. First, in the presence of a negative externality, the cutoff value r^I above which the innovator accepts to sell the good is increasing in the number of bidders N and in the level of the externality α. The intuition is the following. Selling a license generates $(N-1)\alpha$

[12] This proposition is simply the extension of the standard auction with negative externalities to the case of a multi-unit auction. See Jehiel et al. (1996) and Brocas (2005) for the one-object case.

negative externalities in the industry. This affects the value of the item to the innovator, which becomes his intrinsic valuation (i.e. 0) plus this amount. The price is then modified accordingly. Second, since there is no quantity restrictions, the innovator is interested in attracting as many licensees as possible (provided their willingness to bid above r^I), so N licenses are offered for sale.[13] Third, in order to induce full entry and extract as many rents as possible, the seller designs a procedure that penalizes a firm who does not participate with his worst outside option, namely $-\alpha(N-1)$. As shown in part (ii) of the proposition the simplest way to make this threat credible is by committing to give a license for free to each participant when at least one of the producers does not participate in the auction.[14]

At this point, it is useful to determine a simple way to implement the optimal mechanism described in Proposition 1.

Corollary 1 *The optimal auction can be implemented by a sealed-bid auction where participants pay an entry fee* $c^I = \alpha(N-1)F(r^I)$ *and the reserve price is* r^I*.*

Proof: *See APPENDIX A2.*

This is a direct consequence of Proposition 1. First, given that there is no quantity restriction in the number of licenses, producers do not compete among each other: each firm with a bid above the reserve price r^I will obtain a license. As a result no firm will submit a bid strictly above r^I (in which case, first or second price auctions are equivalent). Second, the presence of externalities generates rents that can be extracted by the seller at no cost. This results from the bidders' willingness not only to acquire the license but also to prevent others from getting it. As a consequence, the seller can set

[13] The analysis can be extended to the case of "congestion", that is when producers leave the market if more than k' ($< N$) competitors obtain the license. In that case, the allocation rule for licenses consists in offering k' licenses for sale and threatening agents with their worst outside option, namely $-\alpha k'$. The shape of the reserve price remains unchanged but the rents that can be extracted by the seller decrease.

[14] Naturally, there exist other mechanism to induce full entry, such as resorting to third parties. However, for any of these mechanisms to work, the auctioneer must be able to commit which, as pointed before, is a strong assumption: if some firm does not show up, the innovator will have ex-post incentives not to give away licenses for free. Absent a credible commitment device, there might be a collusive behavior among producers who can jointly decide not to enter. The results when this assumption is relaxed are analyzed extensively in Brocas (2003). The basic result in that paper is that, in the absence of commitment, the optimal auction is modified. However, it keeps the same qualitative properties as long as the producers' profits are not entirely dissipated by the negative externalities (that is, as long as the valuations v_i are large relative to α).

an entry fee that is paid even by non-acquirers. This fee is increasing in both the level of the externality α and the size of the industry N, because the outside option is inversely proportional to these two parameters. Also, more revenue can be raised with the entry fee if the innovator commits to sell fewer licenses, which is obtained by setting a higher reserve price r^I. Overall, the level of the externality affects positively the expected revenue of the seller and therefore his incentives to exert effort in order to obtain the innovation. Formally, denote by R^I the expected revenue raised in the auction under the innovator's optimal mechanism. Using (4), we have:

$$R^I = \int_{r^I}^{\overline{v}} \sum_{i=1}^{N} \left[v_i - \alpha(N-1) - \frac{1-F(v_i)}{f(v_i)} \right] f(v)dv + \alpha(N-1)N \tag{5}$$

The innovator's ex-ante utility is:

$$V = \pi(e)R^I - \psi(e) \tag{6}$$

and therefore, he selects the effort e^I that solves:

$$\pi'(e^I)R^I = \psi'(e^I)$$

so that his equilibrium expected utility is:

$$V^I = \pi(e^I)R^I - \psi(e^I)$$

Combining (3) and Proposition 1, we get that producer i's equilibrium surplus is:

$$u_i^I(v_i) = \int_{r^I}^{v_i} X_i^I(s)ds - \alpha(N-1)$$

and the expected value of the innovation for the pool of producers is:

$$\begin{aligned} U^I &= \pi(e^I) \int_{\underline{v}}^{\overline{v}} \sum_{i=1}^{N} u_i^I(v_i)\, f(v)dv \qquad (7) \\ &= \pi(e^I) \left[\int_{r^I}^{\overline{v}} \left(\sum_{i=1}^{N} \int_{r^I}^{v_i} X_i^I(s)ds \right) f(v)dv - \alpha(N-1)N \right] \end{aligned}$$

Last, the equilibrium expected welfare of the industry is given by:

$$W^I = U^I + V^I$$

$$= \pi(e^I) \int_{r^I}^{\overline{v}} \sum_{i=1}^{N} \Big[v_i - \alpha(N-1) \Big] f(v) dv - \psi(e^I)$$

Since the research laboratory does not internalize the value of his innovation on producers, industry welfare will not be maximized. As an extreme case, note that if the externality is sufficiently high ($\alpha(N-1) > \overline{v}$ so that $r^I = \overline{v}$) total welfare is negative ($W^I = -\psi(e^I)$): the innovator is willing to exert research effort because it allows him to extract rents for not selling the innovation to anyone. As a result, effort results in transfers from one party to another but, from a social viewpoint, it is a pure waste.[15]

Remark 3. At this stage, it is useful to draw a parallel between our results and pricing practices. The optimal mechanism (Proposition 1) tells us that the best pricing policy consists in allocating licenses in exchange of a high price and extracting payments from non acquirers. This last part reflects the fact that producers are ready to pay the innovator for not selling the license to their rivals. In such a mechanism, participating (and making a payment anyway) buys each producer a chance of not suffering externalities (since the minimum price of a license is high and many producers may not afford it). Corollary 1 highlights a simple way to implement the optimal mechanism: the entry fee is paid by all bidders, and the reserve price is high enough so that only a small fraction of bidders can acquire the license, which make bidders willing to pay the entry fee in the first place. In practice, other types of mechanisms can be used (e.g., vertical contracting, bargaining), but the same features remain: the innovator finds it profitable to receive payments to not trade the license and to increase accordingly the price at which he trades it. Those practices are common in vertical contracting[16] (e.g. supermarkets organize tournaments between food suppliers in which all pay non refundable fees in the first place)[17], yet sometimes regulated. Naturally, these regulations prevent the implementation of the optimal auction, and the revenue becomes smaller. However, they do not distort the incentives to pay to prevent rivals from getting the good, and the seller can always take advantage of it[18] by

[15]This case is more a theoretical curiosity than a real-life case. Yet, it illustrates in a caricatured way the common situation in which the innovator's biggest source of income comes from his commitment to restrict the number of licenses sold.

[16]See Katz (1989).

[17]In Europe in particular, contracts between supermarkets and retailers specify a series of fees without real benefits. See Competition Commission report (2000).

[18]In the case of auctions, three tools are available: entry fees, reserve prices and number of licenses for sale. Our result suggests that the number of licenses for sale has to be the highest possible as long as the reserve price can be high and entry fees can be set. If the

making the pool of producers paying high prices. This naturally goes with selling only a few licenses in equilibrium.

In the next section, we concentrate on the case where a regulator organizes the R&D activity by fixing the rules of the auction game and specifying the innovator's reward.

4 The regulated industry

Suppose that a government agency (she) can regulate the research activity and dissemination of knowledge. More precisely, we assume that licenses are, just as before, auctioned to producers. The innovator keeps the revenues generated in the auction. However, it is now the regulator who determines the optimal allocation rule of licenses. Furthermore, we assume that the regulator can also subsidize (or tax) the innovator for his research activity in order to increase (or decrease) his total revenue. This subsidy (or tax) is financed by costly public funds: each unit of money spent by the regulator is raised through distortionary taxes and costs society $(1 + \lambda)$ units, where $\lambda \geq 0$. Its main purpose is to provide incentives to the innovator to select a research effort close to the socially optimal level.

Summing up, the regulator uses two mechanisms to intervene in the activity of the innovator: costly transfers and selection of allocation rule of licenses. The payoff of the innovator comes from two different sources: direct revenue of the auction and (positive or negative) transfer from the regulator.

4.1 Optimal allocation of licenses

We denote by $T(v)$ the *total* ex-post payoff of the research laboratory if his innovation succeeds. Naturally, it depends on the revenues of the auction, and therefore on the vector of valuations announced by the producers (which, in equilibrium and by the revelation principle, coincide with their true valuation). We assume that the innovator faces a limited liability constraint and that his expected transfer must be non-negative. Since it is costly for the regulator to leave rents, the innovator receives no payment if his innovation fails and an

seller cannot use one of these tools, he can adjust the two others in order to increase his revenue. In a world of non optimal contracts, this may result in decreasing the number of licenses for sale in order to force players to bid more aggressively.

expected total payoff $T \geq 0$ if his innovations succeeds, where:[19]

$$T = \int_{\underline{v}}^{\overline{v}} T(v) f(v) dv$$

The innovator's ex-ante utility is the analogue of (6) to the regulated case, that is:

$$\tilde{V} = \pi(e)T - \psi(e) \tag{8}$$

The expected value of the innovation for the pool of producers is similar to (7). However, the difference between the innovator's total payoff T and the revenue obtained with the auction $\sum t_i$ has to be raised through distortionary taxation (with the extra cost λ). Formally:

$$\tilde{U} = \pi(e) \left[\int_{\underline{v}}^{\overline{v}} \sum_{i=1}^{N} u_i(v_i) f(v) dv - (1+\lambda)\Big(T - \int_{\underline{v}}^{\overline{v}} \sum_{i=1}^{N} t_i(v) f(v) dv \Big) \right] \tag{9}$$

As in the previous section, the welfare of the industry is the sum of the innovator's and the producers' utility $\tilde{W} = \tilde{U} + \tilde{V}$. Once again using (2), (3) and the same integration by parts technique as before, we can rewrite the expected welfare of the industry as:

$$\tilde{W} = \pi(e) \Big[\int_{\underline{v}}^{\overline{v}} \sum_{i=1}^{N} X_i(v) \Big((1+\lambda)(v_i - \alpha(N-1)) - \lambda \frac{1-F(v_i)}{f(v_i)} \Big) f(v) dv + \lambda N u_i(\underline{v}) - \lambda T \Big] - \psi(e)$$

At this stage, we can characterize the first part of the intervention, namely the optimal mechanism selected by the regulator to allocate licenses among producers. The regulator's optimization problem consists of maximizing the welfare of the industry $\tilde{W}$ under the producers' constraints (IC_1)-(IC_2)-(IR_i)-(F_0)-(F_1). The result is the following.

Proposition 2 *The optimal licensing mechanism from the regulator's point of view entails:*
(i) *If $n = N$, the mechanism is direct, $k^R = N$ licenses are offered for sale and allocated according to the following selection rule:*

[19] If the quality of the innovation is not observable, the regulator must offer an incentive scheme in order to induce the innovator to reveal the quality in equilibrium. In that case, inefficiencies result from the presence of informational rents but the results we obtain in this section remain qualitatively unchanged.

$$X_i^R(v) = \begin{cases} 1 & if \quad v_i \geq r^R \\ 0 & otherwise \end{cases}$$

where r^R *solves:* $\begin{cases} r^R - \alpha(N-1) - \frac{\lambda}{1+\lambda}\frac{1-F(r^R)}{f(r^R)} = 0 & if \ \alpha(N-1) < \overline{v} \\ r^R = \overline{v} & otherwise \end{cases}$

(ii) *If* $n < N$*, each participant receives one license for free.*

Proof: *See APPENDIX A1.*

The optimal mechanism selected by the regulator is very closely related to the one chosen by the innovator himself: as before, all the licenses are offered for sale and every producer with a valuation above a certain threshold obtains one. The only difference between the mechanisms presented in Propositions 1 and 2 concerns the amount of dissemination of knowledge. From a social point of view, more producers should enjoy the license than optimal from the innovator's private interest. This is reflected in a lower reserve price ($r^R < r^I$). Note however that, as the cost of transferring funds from producers to innovator increases, intervention of the regulator becomes more costly and therefore less desirable. When the distortionary cost of taxation is prohibitively high, then the regulator does not intervene and the mechanism implemented is the same as in Proposition 1 (formally, $\partial r^R/\partial\lambda > 0$ and $\lim_{\lambda\to+\infty} r^R(\lambda) = r^I$). Not surprisingly, the implementation follows the same lines as in section 3.

Corollary 2 *The optimal auction can be implemented by a sealed-bid auction where participants pay an entry fee* $c^R = \alpha(N-1)F(r^R)$ *and the reserve price is* r^R*.*

Proof: *See APPENDIX A2.*

Denote by R^R the expected revenue raised in the auction under the regulator's optimal mechanism. Using (4), we have:

$$R^R = \int_{r^R}^{\overline{v}} \sum_{i=1}^{N} \left[v_i - \alpha(N-1) - \frac{1-F(v_i)}{f(v_i)} \right] f(v)dv + \alpha(N-1)N \qquad (10)$$

Given that r^I solves $r^I - \alpha(N-1) - \frac{1-F(r^I)}{f(r^I)} = 0$ and that $r^R < r^I$, it is immediate from (5) and (10) that $R^R < R^I$.[20] In other words, and by definition, selling more licenses than optimal from the innovator's viewpoint reduces the total payoff obtained in the auction.

[20] Also, given that $\partial r^R/\partial\lambda > 0$, we have $\partial R^R/\partial\lambda > 0$ and $\lim_{\lambda\to+\infty} R^R(\lambda) = R^I$.

4.2 Regulator's transfer and optimal research effort

In order to analyze the socially optimal effort, we are going to assume that, from an ex-ante viewpoint, the innovation is beneficial for all parties (innovator and producers), which implies that the regulator is interested in promoting effort in the research activity. For this to occur, the externality must be "sufficiently high" so that the revenue raised by the innovator in the auction under the optimal mechanism imposed by the regulator is positive (Assumption 4(i)). However, it also has to be "sufficiently small" so that each producer is better-off if the innovation is successful and licenses are auctioned (Assumption 4(ii)).[21] The conditions on α and N are summarized in the following assumption.

Assumption 4

(i) $R^R > 0 \;\; \forall \lambda \;\; \Leftrightarrow \int_{\alpha(N-1)}^{\overline{v}} \sum_{i=1}^{N} \left[v_i - \alpha(N-1) - \frac{1-F(v_i)}{f(v_i)} \right] f(v)dv + \alpha(N-1)N > 0.$[22]

(ii) $\int_{\underline{v}}^{\overline{v}} \sum_{i=1}^{N} u_i(v_i) f(v_i) dv_i > 0 \; \forall \lambda \;\; \Leftrightarrow \;\; \int_{r^I}^{\overline{v}} \sum_{i=1}^{N} \frac{1-F(v_i)}{f(v_i)} f(v)dv - \alpha(N-1)N > 0.$[23]

In words, part (i) ensures that the innovator gets a positive payoff from the auction and part (ii) guarantees that the expected rents left to the pool of producers are also positive.

For expositional ease, let us now define the gross industry value of the innovation as:

$$S(\lambda) = \int_{r^R(\lambda)}^{\overline{v}} \sum_{i=1}^{N} \Big((1+\lambda)(v_i - \alpha(N-1)) - \lambda \frac{1-F(v_i)}{f(v_i)} \Big) f(v)dv + \lambda\alpha(N-1)N \tag{11}$$

From Proposition 2 and the definition of $\tilde{W}$, we thus have:

$$\tilde{W} = \pi(e)\Big[S(\lambda) - \lambda T \Big] - \psi(e) \tag{12}$$

[21]Recall that if $\alpha(N-1) > \overline{v}$, then $r^I = \overline{v}$: no producer gets the license but all of them pay an entry fee $c^I = \alpha(N-1)$. Our assumption rules out cases like this one.

[22]Given $\partial r^R / \partial \lambda > 0$ and $r^R(+\infty) = r^I$, we only need to check $R^R > 0$ for $\lambda = 0$, that is when $r^R = \alpha(N-1)$.

[23]Given $\partial r^R / \partial \lambda > 0$ we only need to check that the expected rents left to consumers are positive when $\lambda \to +\infty$, that is when $r^R = r^I$.

Recall that the regulator cannot force the innovator to accept her preferred transfer and allocation rule. In other words and given (8), the contract offered to the innovator must satisfy the following participation constraint:

$$\pi(e)\,T - \psi(e) \geq 0 \tag{IR}$$

Suppose, as a benchmark case, that the regulator can monitor the effort of the innovator. She will then induce the innovator to undertake the socially optimal effort level, that is the effort $e^\star$ that maximizes industry welfare $\tilde{W}$ under the innovator's participation constraint (IR). From (12), it is immediate to see that transfers to the innovator are socially costly. Therefore, the participation constraint (IR) will be binding, that is $T = \psi(e)/\pi(e)$. If we insert this value of the transfer in the regulator's objective function (12), we can characterize the main properties of the optimal effort. These are summarized in the following lemma.

Lemma 1 *If the research effort is observable, its optimal level $e^\star$ is such that:*

$$\pi'(e^\star)S(\lambda) = (1+\lambda)\psi'(e^\star)$$

where $\partial e^\star(\lambda)/\partial\lambda < 0$ *and* $\lim_{\lambda\to+\infty} e^\star(\lambda) = e^I$.

Proof: *See APPENDIX A3.*

Under complete information, the optimal effort is always greater than the effort implemented by the 'non-regulated' innovator. This comes from the fact that the innovator does not internalize the social benefit of the innovation, that is the effect of his effort choice on the welfare of producers. As the social cost of public funds increases, intervention by the regulator becomes more costly and therefore less interesting. When the cost of regulation is prohibitively high ($\lambda \to +\infty$), the regulator simply gives the innovator full responsibility of his acts ($r^R(\infty) = r^I$ and $e^\star(\infty) = e^I$).

To be more realistic, one must assume that the regulator cannot monitor the level of effort exerted by the innovator. In this situation, the innovator will select the effort that maximizes his utility, given by (8). This means that the contract offered by the regulator to the innovator must satisfy not only the participation constraint (IR), but also the following moral hazard constraint:

$$\pi'(e)\,T = \psi'(e) \tag{MH}$$

The maximization of the industry welfare $\tilde{W}$ under the participation and moral hazard constraints of the innovator (IR)-(MH) yields the following optimal second-best research effort and total transfer in case of success.

Proposition 3 *If the research effort is non-observable, its optimal level e^R is such that:*

$$\pi'(e^R)S(\lambda) = (1+\lambda)\psi'(e^R) + \lambda\frac{\pi(e^R)}{\pi'(e^R)}\left(\psi''(e^R) - \pi''(e^R)\frac{\psi'(e^R)}{\pi'(e^R)}\right)$$

where $e^R(0) = e^\star(0)$, $e^R(\lambda) < e^\star(\lambda)$ for all $\lambda > 0$, $\partial e^R(\lambda)/\partial\lambda < 0$ and $\lim_{\lambda\to+\infty} e^R(\lambda) < e^I$.

The expected transfer when the innovation succeeds is $T^R = \dfrac{\psi'(e^R)}{\pi'(e^R)}$, with $\partial T^R/\partial\lambda < 0$.

Proof: *See APPENDIX A3.*

When effort is not observable and the innovator has a limited liability constraint, the regulator is forced to give rents to the innovator in order to encourage him to obtain a (socially valuable) innovation.[24] However, these rents are socially costly due to the positive shadow cost of public funds. Hence, in order to decrease them, the regulator solves the usual trade-off efficiency vs. rents with a downward distortion of effort. Naturally, as the cost of taxation λ increases, encouraging effort becomes relatively more costly and therefore less desirable. As a result the transfer to the innovator in case of success also decreases.

Let us denote by s^R the net transfer (a subsidy if positive, a tax if negative) from the regulator to the innovator for the research activity. Formally, we have:

$$T^R \equiv R^R + s^R$$

where the expression of T^R is presented in Proposition 2 and that of R^R in equation (10). One might wonder whether, in the optimal regulation mechanism, the innovator should be subsidized or taxed for his research activity. The next proposition deals with this issue.

Proposition 4 *There exists a threshold $\overline{\lambda}$ such that $s^R \gtreqless 0$ if and only if $\lambda \lesseqgtr \overline{\lambda}$.*

Proof: *See APPENDIX A4.*

[24]Obviously, in the absence of a limited liability constraint, the first-best effort $e^\star$ can be achieved even under incomplete information: the regulator simply needs to punish sufficiently the innovator when his research activity fails.

As mentioned above, when λ increases, it is more costly for the regulator to encourage effort and therefore less suitable to offer transfers T^R. At the same time, we know from equation (10) that the revenue raised with the auction increases with λ, precisely because the regulator implements a selling mechanism closer to the one preferred by the innovator (that is, the revenue maximizing one). Both effects imply that the net transfer s^R offered by the regulator for a successful innovation will be inversely related to λ. Stated differently, as λ increases, the regulator optimally substitutes the costly financing (transfers raised through public funds) with the costless one (revenue of the auction). Naturally, this comes at the expense of an increase in the reserve price r^R and therefore a decrease in the dissemination of knowledge, as fewer licenses are sold. Note that when $\lambda = \overline{\lambda}$, the regulator intervenes in the design of the license allocation mechanism but not in the research activity ($s^R = 0$, so the innovator's sole source of income is the auction revenue). Last, for costs of public funds above that threshold, the innovator is taxed for his research activity, although his payment is compensated by the payoffs obtained in the auction.

Remark 4. Note that negative externalities are not necessarily socially detrimental: one of the parties –the innovator– greatly benefits from them. However, externalities induce some perverse effects, the most striking one being the willingness of the laboratory to invest resources in order to obtain an innovation that will never (or rarely) be marketed. The aim of the regulator's intervention is only to mitigate the inefficiencies that occur because parties do not integrate the effect of their actions on other parties' welfare.

4.3 Consumer welfare

So far we have neglected the impact of licensing on consumer welfare to better isolate the effect of externalities between producers. From the perspective of producers, licensing generates unambiguously negative externalities, even though the size of these externalities will vary from market to market. However the effect of licensing on consumer welfare is a priori unclear. Indeed, consumer welfare may increase or decrease, depending on the kind of innovation and the type of market competition. On the one hand, producers may become more competitive, which translates into a reduction of prices and an unambiguous increase in consumer surplus. This may be the case if the discovery is a process innovation that diminishes the cost of production in a non-drastic way. On the other hand, the market may become more segmented, so that each licensee has local monopoly power on a given segment, in which case consumers may have to purchase goods at higher prices and reduce the quantities consumed. In this subsection, we want to address these issues and provide some qualitative prescriptions.

To capture these effects, we assume that the innovation induces an externality on consumers whenever a license is sold. We denote this externality by a. Therefore, the expected consumer surplus is simply the total expected externality

$$\tilde{CS} = \int_{\underline{v}}^{\overline{v}} \sum_{i=1}^{N} a X_i(v) f(v) dv.$$

Expected social welfare $\tilde{Z}$ is simply the sum of the innovator's ex-ante utility $\tilde{V}$, the expected value of the innovation for the pool of producers $\tilde{U}$ and consumer surplus $\tilde{CS}$, or said differently $\tilde{Z} = \tilde{W} + \tilde{CS}$. Using (2) and (3) and rearranging terms, total expected social welfare can be written as:

$$\tilde{Z} = \pi(e)\Bigg[\int_{\underline{v}}^{\overline{v}} \sum_{i=1}^{N} X_i(v)\Big((1+\lambda)(v_i - \alpha(N-1)) + a - \lambda \frac{1-F(v_i)}{f(v_i)}\Big) f(v) dv + \lambda N u_i(\underline{v}) - \lambda T\Bigg] - \psi(e).$$

Note that the analysis in the previous subsections is obtained for $a = 0$. Given the analogy with the previous section, it is immediate to see that the optimal licensing mechanism from the perspective of social welfare is similar to the one characterized in Proposition 2 except that the threshold above which the license is granted is now r^{RS} that solves

$$r^{RS} - \alpha(N-1) + \frac{a}{1+\lambda} - \frac{\lambda}{1+\lambda}\frac{1-F(r^{RS})}{f(r^{RS})} = 0,$$

and is such that $r^{RS} \lesseqgtr r^R$ if $a \gtreqless 0$. Compared to the previous subsection, the regulator will promote more (resp. less) dissemination of knowledge when $a > 0$ (resp. $a < 0$). At equilibrium the gross social value of the innovation is $Y(\lambda) = S(\lambda) + \int_{r^{RS}(\lambda)}^{\overline{v}} \sum_{i=1}^{N} a f(v) dv$ and therefore $Y(\lambda) \gtreqless S(\lambda)$ if $a \gtreqless 0$. Again, it is immediate that the optimal research efforts under complete and incomplete information respectively are such that $e^{*S} \gtreqless e^*$ if $a \gtreqless 0$ and $e^{RS} \gtreqless e^R$ if $a \gtreqless 0$. Compared to our results in the previous subsection, positive (negative) externalities on consumers will simply induce the regulator to encourage (discourage) the innovator to exert effort.

Overall, taking consumer welfare into account modifies the results obtained before only quantitatively. When the innovation is valued positively by consumers ($a > 0$), a benevolent regulator wants to promote higher research effort and dissemination compared to a regulator who cares only about the welfare of the industry. By contrast, when the innovation is detrimental for consumers ($a < 0$), the regulator prefers to reduce both effort and dissemination.

5 How does licensing perform?

In this section, we compare the two regimes analyzed in sections 3 and 4. For the sake of simplicity, we assume the value of the innovation to consumers is $a = 0$ in the next subsections.[25]

5.1 Is regulation welfare improving?

Public intervention is beneficial because it induces the internalization of the externalities generated in the economy. However, it is also socially costly since subsidies are raised through public funds. Therefore, the performance of regulation with respect to welfare is affected by the size of the shadow cost of public funds. The standard analyses in regulation theory show that the benefits of intervention vanish (or become negative) when this cost is sufficiently high. Our next result shows that this is not true in our setting.

Corollary 3 *Regulation always increases welfare, independently of the cost* λ.

Proof: *See APPENDIX A5.*

Our particular regulatory scheme has two components: costly transfers of public funds and design of the allocation mechanism of licenses. The regulatory agency resorts to the subsidy regime to encourage effort of the innovator only when λ is reasonably small. On the contrary, when λ is high, the regulator does not want to give subsidies. She finances the research activity with the revenue of the auction, and taxes the innovator in order to redistribute resources to the producers (see Proposition 4).

Stated differently, the optimal mechanism and effort from the innovator's viewpoint $\{X_i^I, r^I, e^I(X_i^I, r^I)\}$ will never maximize welfare. The regulator can always intervene on the auction mechanism $\{X_i^R, r^R\}$ at no cost for society. Naturally, this will affect the effort selected by the innovator $e^I(X_i^R, r^R)$. However, there is always room to improve welfare without incurring in transfers. Not that this reasoning does not imply that, in equilibrium, the regulator will indeed avoid the costly transfers: as shown in Proposition 4, $s^R = 0$ only when

[25]As shown in subsection 4.3., taking consumers' surplus into account only modifies our results quantitatively.

$\lambda = \overline{\lambda}$.[26] To sum up, the degree of freedom given by the two mechanisms at hand (transfers and auction) makes public intervention always beneficial for the industry relative to a standard licensing mechanism selected by the innovator.[27]

5.2 Intensity of research

Economic theory suggests that, in general, ex-post policies such as patents and licenses do not provide optimal incentives for research and development. Since they are rooted in the intellectual property concept, these mechanisms implicitly put a higher weight in the welfare of innovators than in the welfare of the other agents of the economy. Innovators do not internalize the effects of their choices on those agents, so other things equal, they invest an inefficiently low amount of resources in their research activity.[28] A natural solution to decrease these market inefficiencies is the use of subsidies to research. In section 4, we have shown that encouraging effort is actually a socially efficient way to reconcile public and private interests in the absence of informational asymmetries ($e^{\star}(\lambda) > e^I$ for all λ, see Lemma 1) or when regulation is costless ($e^R > e^I$ if $\lambda = 0$, see Proposition 3). However, as the next proposition shows, the optimal second-best policies under asymmetric information and costly transfers do not always dictate a higher effort level than the one selected by a non-regulated innovator.

Proposition 5 *There exists a threshold $\hat{\lambda}$ $(< \overline{\lambda})$ such that $e^R(\lambda) \gtreqless e^I$ if and only if $\lambda \lesseqgtr \hat{\lambda}$.*

Proof: *See APPENDIX A6.*

When the cost of public funds is sufficiently small ($\lambda < \hat{\lambda}$), the regulator finds it optimal to subsidize heavily the research activity of the innovator in order to increase his incentives to exert effort and disseminate knowledge (formally, $s^R > 0$ and $T^R > R^I$ so that $e^R > e^I$). For intermediate values of the

[26] Nevertheless, it should be clear that Corollary 3 crucially depends on the fact that only taxes and subsidies are costly. Indeed, consider the following alternative timing. The regulator receives the innovation from the research laboratory in exchange of a transfer entirely raised through taxation, and then sells licenses to the producers. In this case, there is no substitution effect between costly subsidy and costless auction revenue. As a result, all the benefits of intervention vanish for sufficiently high values of λ.

[27] Of course, this is also true in the setting analyzed in subsection 4.3.

[28] Naturally, other factors (like competition in the research market) may push innovators to invest an inefficiently high amount of resources. See Reinganum (1989), as well as the literature on patent races (e.g. Loury (1979), Lee and Wilde (1980).

shadow cost ($\lambda \in [\hat{\lambda}, \overline{\lambda}]$), positive transfers become less desirable: the regulator faces a trade-off between the social gain of the innovation and the distortionary cost of taxation. As a result and given Proposition 4, she still subsidizes the research activity but sets a transfer that does not fully compensate the innovator for his loss in the auction revenue. The innovator reacts by exerting less effort than in the non-regulated case (formally, $s^R > 0$ and $T^R < R^I$ so that $e^R < e^I$).[29] Last, when the cost of public funds are sufficiently high ($\lambda > \overline{\lambda}$), the regulator prefers to tax the innovator for his research activity in order to compensate the producers. This reduces dramatically the incentives of the research laboratory: his revenue from the auctions is lower than in the non-regulated case and he also has to pay if the innovation succeeds. His effort is then greatly reduced, although it remains positive (formally, $s^R < 0$ and $T^R << R^I$ so that $e^R << e^I$). These three cases are graphically represented in Figure 2.[30]

[29]The reason why $\overline{\lambda} > \hat{\lambda}$ is simple. By definition, the innovator chooses an effort e^I when his total payoff if the innovation succeeds is R^I. Under regulation, the revenue of the auction is R^R ($< R^I$). Hence, in order to induce e^I, the regulator has to compensate the innovator with a subsidy $s^R = R^I - R^R > 0$. Hence, under regulation and budget balance ($s^R = 0$) the innovator exerts less effort than under no-regulation.

[30]Note that if we compare the regulation-free environment with the optimal regulation from the perspective of total welfare, the result remains qualitatively unchanged: only the threshold below which regulation promotes more effort takes a different value (higher or smaller depending on whether the externality on consumers is positive or negative).

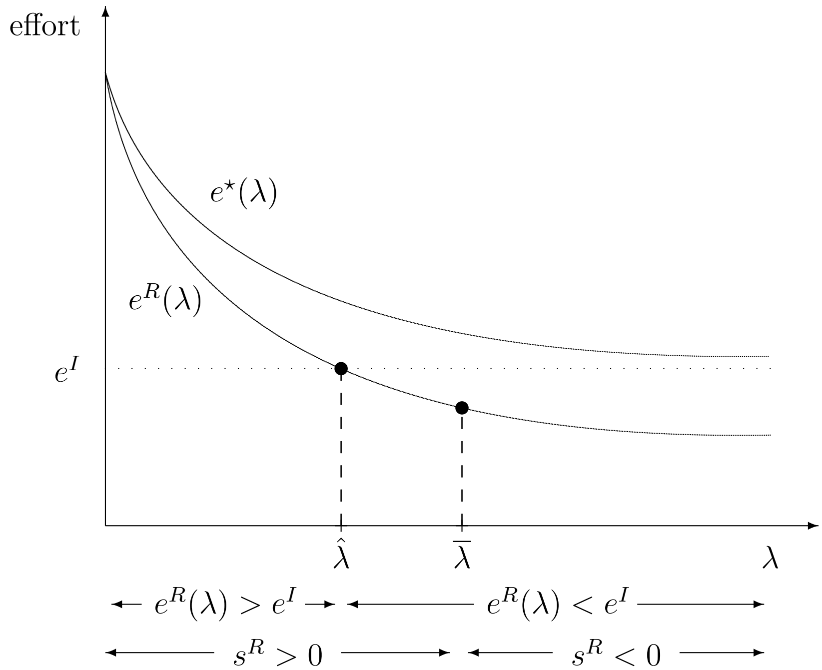

Figure 2. Optimal effort

5.3 Regulation and competition: the effects of antitrust

In the presence of negative externalities, an anticompetitive risk stems from the fact that the innovator can fix high royalties (formally in our model, a high reserve price), so that many producers do not get licenses and therefore are "excluded" from ex-post competition. We have seen in section 4 that the regulator always aims at fostering the dissemination of knowledge, by decreasing the reserve price ($r^R < r^I$) once the innovation has been obtained. However, intervention also affects the research effort and therefore the likelihood of innovating. It is therefore interesting to determine how regulation affects both the ex-ante expected number of licenses sold and the ex-post licensing once the innovation has been successful. To analyze this issue, we denote by $x^I = N[1 - F(r^I)]$ and $x^R(\lambda) = N[1 - F(r^R(\lambda))]$ the expected number of licenses sold once an innovation has been achieved in the decentralized and regulated environments, respectively. The ex-ante number of licenses in both cases is then $\pi(e^I)x^I$ and $\pi(e^R(\lambda))x^R(\lambda)$, and we have the following result.

Proposition 6 (i) *$x^R > x^I$ for all λ, α and N.*

(ii) *There exists* $\tilde{\lambda}$ *such that* $\pi(e^R(\lambda))x^R(\lambda) \gtrless \pi(e^I)x^I$ *if and only if* $\lambda \lessgtr \tilde{\lambda}$.

Proof: *See APPENDIX A7.*

Part (i) reflects the idea that the regulator always selects a reserve price smaller than optimal from the innovator's perspective, in order to increase the dissemination of knowledge once the innovation is achieved. However, part (ii) states that when the shadow cost of public funds is very high, there will be less dissemination from an ex-ante perspective under regulation than under no-regulation. The reason is simply that, when transfers are very costly, it is optimal for the regulator to tax the innovator for his research activity and redistribute the benefits with the producers. As a compensation to the innovator, the regulator selects an allocation mechanism close to the one that maximizes the revenues of the auction. Overall, the ex-post dissemination is close to the no-regulation case whereas the incentives to effort –and therefore the probability of innovation– are greatly reduced due to taxation of the research activity. In any case, it is interesting to notice that, as soon as $\lambda > \hat{\lambda}$, regulation implies fewer innovations but more licenses if the innovation succeeds.

To illustrate this idea, let us consider the following numerical example. Suppose that valuations are uniformly distributed between 0 and 1 (i.e. $v_i \sim U[0,1]\ \forall i$).[31] Using simple algebra, we obtain the following expressions for the reserve prices and expected number of licenses sold after an innovation has succeeded as a function of the externality α and the cost of public funds λ:

$$r^I(\alpha) = \frac{\alpha(N-1)+1}{2} \quad \text{and} \quad r^R(\lambda,\alpha) = \frac{\alpha(N-1)(1+\lambda)+\lambda}{1+2\lambda}$$

$$x^I(\alpha) = \frac{N[1-\alpha(N-1)]}{2} \quad \text{and} \quad x^R(\lambda,\alpha) = \frac{N(1+\lambda)[1-\alpha(N-1)]}{1+2\lambda}$$

Note that, for all $\alpha(N-1) < 1$, we have $r^R(\lambda,\alpha) < r^I(\alpha)$ and $x^R(\lambda,\alpha) > x^I(\alpha)$. One can notice that if the cost of public funds is arbitrarily small, the regulator is willing to sell on expectation twice as many licenses as the innovator, independently of the level of the externality and the number of producers. The difference in the optimal dissemination of knowledge decreases as λ increases and vanishes when λ is arbitrarily large.[32] The table below provides some comparative statics.

[31] The restriction $\alpha(N-1) < \overline{v}$ translates into $\alpha(N-1) < 1$.

[32] Formally, $x^R(\lambda,\alpha) = \frac{2+2\lambda}{1+2\lambda}x^I(\alpha)$ so $\lim_{\lambda\to 0} x^R(\lambda,\alpha) = 2x^I(\alpha)$ and $\lim_{\lambda\to+\infty} x^R(\lambda,\alpha) = x^I(\alpha)$. Also note that in the absence of externalities and when transfers are not socially costly, ($\alpha = 0$ and $\lambda = 0$), the regulator wants to sell all the licenses and the innovator only half of them ($x^R(0,0) = N$ and $x^I(0) = N/2$).

	$N=2$	$N=3$	$N=4$	$N=5$	$N=8$	$N=10$
$x^I(0.1)$	0.90	1.20	1.40	1.50	1.20	0.50
$x^R(1.0,0.1)$	1.20	1.60	1.86	2.00	1.60	0.66
$x^R(0.3,0.1)$	1.46	1.95	2.27	2.43	1.95	0.82
$x^R(0.1,0.1)$	1.65	2.20	2.56	2.75	2.20	0.91

It is also interesting to notice that the performance of regulation decreases with α. Indeed, fewer licenses are optimally sold as the externality increases, both from the regulator's and the innovator's viewpoint. However, dissemination decreases at a higher rate when the innovator is regulated (i.e. $\left|\frac{\partial x^R}{\partial \alpha}\right| > \left|\frac{\partial x^I}{\partial \alpha}\right|$). This comes from the fact that, when α increases, the reserve price in the regulated industry increases faster than in the non-regulated one. The reason is simply that, with higher externalities, the regulator is less prone to finance research with public funds rather than with the revenue of the auction.

The use of entrance fees and high reserve prices (or, equivalently, high royalties paid by those who get licenses) reduces dramatically the dissemination of knowledge: only a few number of firms get the innovation and the initial oligopoly structure vanishes. Both in Europe and the US, antitrust authorities are aware of this phenomenon. To combat low dissemination, the authorities specify some restrictions in the type of licensing agreements that can be signed.[33] Such intervention roughly corresponds in our model to a "partial regulation" regime, that is a situation in which the government agency specifies the rule for allocating licenses but does not resort to subsidies or taxes in order to affect the research activity of the innovator. Our last proposition characterizes the optimal allocation rule of licenses selected by the regulator and the effort chosen by the innovator in this partial intervention case. Formally, the regulator maximizes the welfare of the industry $\tilde{W}$ under the producers' constraints (IC_1)-(IC_2)-(IR_i)-(F_0)-(F_1), the innovator's constraints (IR)-(MH), and the no-transfer between producers and innovator constraint $T^R = R^R$.

Proposition 7 *If the regulator can only select the allocation of licenses rule, her optimal mechanism is the same as in Proposition 2 except that $r^R(\lambda)$ is replaced by $\hat{r} \in (r^R(0), r^I)$. The innovator selects an effort $\hat{e} < e^I$.*

[33] The European Commission regulation applies the Article 85 of the Treaty to certain categories of patent or know-how licensing agreements if competitiveness is affected. In addition, it encourages the sale of one license per country so that licensees are not direct competitors. This can be viewed as an attempt to reduce the level of negative externalities and then the incentives to charge high royalties.

Proof: *See APPENDIX A8.*

As expected, under the partial regulation regime, ex-post dissemination of knowledge is higher than under no intervention. However, this come at the expense of a lower revenue from the auction, which implies lower incentives for the innovator to exert effort in his research activity. In other words, in the absence of explicit transfers, the regulator trades-off more dissemination of knowledge (obtained with a lower reserve price) vs. less research effort (due to lower revenues of the auction).

As a general conclusion, antitrust policies decrease ex-post anticompetitive risks but, at the same time, also decrease the ex-ante incentives to embark on R&D projects. This means that, in order to be effective, antitrust regulations should be combined with policies aiming at promoting research efforts. One possibility is to subsidize innovators. Our previous results suggest that, as long as the social cost of public funds is not too high, subsidizing research activities and regulating the allocation of licenses improves R&D performance and increases the welfare of the industry. This combination of policies is precisely what we observe in practice. First, as argued above, antitrust authorities supervise the license agreements. Second, firms engaged in R&D activities receive public funds. These subsidies represent 29.9% of the total investment in the US, 34.1% in Canada, 20.7% in Germany and 33.9% in France, just to give a few examples.[34] Furthermore, other forms of subsidies are also widely used. For instance, the European Commission has designed a fiscal regime beneficial to innovation by proposing, inter alia, improvements to the accounting and tax treatment of intangible investment. This kind of public intervention together with a tight regulation of ex-post licensing is precisely what this paper advocates.

6 Concluding remarks

In this paper, we have shown that licensing agreements fail to provide adequate incentives to the provision of effort, do not foster an efficient dissemination of knowledge and lead to anticompetitive risks if they are not closely supervised by public authorities. Indeed, the very presence of negative externalities in the product market allows the innovator to extract payments for reducing the number of licenses sold. In the light of our investigation, we recommend the combination of two policies: an intervention of antitrust authorities directed to decrease the prices at which licenses are sold, and the implementation of

[34]See OECD (1998).

a tax-subsidy system that provides incentives to innovators to exert efficient levels of research effort.

We would like to conclude by pointing out two natural extensions of our basic model. First, the innovator is often also a producer, so his decision to license his innovation trades-off the benefits of obtaining extra revenues with the costs of increasing competition in the product market. More importantly, the quality (or size) of the innovation affects the decision to produce and / or to license innovations. Intuitively, if the innovation is drastic, the innovator is relatively more willing to produce and also to avoid competition in the product market. If the innovation is minor, he is more prone to sell licenses exclusively. Second, negative externalities induce inefficiencies, mainly because the seller is a monopolist in the market for licenses. The inefficiencies would be partly dissipated if several research laboratories were simultaneously allowed to sell licenses. Naturally, this would imply granting patents to more than one innovator, which goes against standard practices in the protection of intellectual property. Our analysis suggests that when externalities in the product market are important, the use of this standard policy should be carefully reconsidered.

APPENDIX

A1. Proof of Propositions 1 and 2.

Proposition 1. Consider the auction with N bidders. The seller aims at decreasing the rents of agents. Consequently, the participation constraint ($\mathrm{IR_i}$) of an agent with valuation $\underline{v}$ is binding, that is $u_i(\underline{v}) = -\alpha(N-1)$. Then, using (4), the revenue of the innovator R is:

$$R = \int_{\underline{v}}^{\overline{v}} \sum_{i=1}^{N} X_i(v) \left[v_i - \alpha(N-1) - \frac{1-F(v_i)}{f(v_i)} \right] f(v)dv + \alpha(N-1)N$$

If $X_i^I(v)$ maximizes R under the remaining constraints, that is (IC_1)-(IC_2)-(F_0)-(F_1), then $\{X_i^I(v), t_i^I(v)\}$ is an optimal auction.[35] Let $l(v_i) \equiv v_i - \alpha(N-1) - \frac{1-F(v_i)}{f(v_i)}$. According to Assumption 2, $l(v_i)$ is increasing in v_i. Consider an auction mechanism for which the seller keeps the good when:

$$\max_i \{ l(v_i) \} < 0$$

and allocates it to each bidder i with a positive $l(v_i)$:

$$l(v_i) \geq 0 \;\Rightarrow\; X_i(v) = 1$$

In particular, this mechanism is such that all bidders can potentially obtain the license, therefore it is such that $k = N$. For any vector of valuations v, this mechanism maximizes:

$$\sum_{i=1}^{N} X_i(v) l(v_i)$$

under constraints (F_0)-(F_1). Hence, it maximizes the seller's revenue under these constraints. Note that (IC_2) is also satisfied: if $\tilde{v}_i < v_i$, then $l(\tilde{v}_i) \leq l(v_i)$ and therefore $X_i(\tilde{v}_i, v_{-i}) \leq X_i(v_i, v_{-i})$. Define r^I as the value of v such that $l(r^I) = 0$. The optimal mechanism is characterized by:

$$X_i(v_i, v_{-i}) = \begin{cases} 1 & \text{if } \; v_i \geq r^I \\ 0 & \text{otherwise} \end{cases}$$

Last, consider the participation decision of firm i when n others decide to

[35] The proof is similar to Myerson (1981).

participate. When $0 \leq n < N-1$, he gets the good for sure and with no payment if he enters and his surplus is $v_i - \alpha n$ whereas if he does not participate is surplus is $-\alpha n$. When $n = N-1$, his utility is $-\alpha(N-1)$ in case of no participation and at least $-\alpha(N-1)$ when he participates.

Proposition 2. It follows exactly the same lines except that the objective function is $\widetilde{W}$ rather than R, so the relevant function is $\tilde{l}(v_i) = v_i - \alpha(N-1) - \frac{\lambda}{1+\lambda}\frac{1-F(v_i)}{f(v_i)}$ rather than $l(v_i)$. Define $r^R(\lambda)$ as the value of v such that $\tilde{l}(r^R(\lambda)) = 0$. Differentiating this expression with respect to λ we have:

$$\frac{\partial \tilde{l}(r^R)}{\partial \lambda} + \frac{\partial \tilde{l}(r^R)}{\partial r^R}\frac{\partial r^R}{\partial \lambda} = 0$$

Since $\frac{\partial \tilde{l}(r^R)}{\partial \lambda} < 0$ and, by assumption 2, $\frac{\partial \tilde{l}(r^R)}{\partial r^R} > 0$, we conclude that $\frac{\partial r^R}{\partial \lambda} > 0$. Last, since $\lim_{\lambda \to +\infty} \frac{\lambda}{1+\lambda} = 1$, we have $\lim_{\lambda \to +\infty} r^R(\lambda) = r^I$. □

A2 Proof of Corollaries 1 and 2.

Corollary 1. The seller offers N licenses. Denote b_i firm i's announcement. If $b_i \geq r^I(\alpha)$, he gets the good with probability 1, whatever his competitors announce. If $b_i < r^I(\alpha)$, he does not get it. Hence, the optimal bidding strategy is $b_i = r^I(\alpha)$ for all i such that $v_i \geq r^I(\alpha)$.

Let Z be the counting variable of i's competitors who have a valuation greater than r^I. Given (2), (3) and the fact that (IR_i) binds at $v_i = \underline{v}$, we have that for all $v_i \geq r^I(\alpha)$, the optimal expected transfers are:

$$E_{v_{-i}}\, t_i(v) = v_i - \alpha \sum_{k=1}^{N-1} k \,\Pr(Z=k) - \int_{r^I}^{v_i} ds + \alpha(N-1)$$

The probability that an agent has a valuation greater than r^I is $1 - F(r^I)$. Therefore, Z follows a binomial distribution with parameters $(N-1, 1-F(r^I))$. Thus:

$$E_{v_{-i}}\, t_i(v) = r^I + \alpha(N-1)F(r^I)$$

Similarly, for all $v_i < r^I$ the optimal expected transfers are:

$$E_{v_{-i}}\, t_i(v) = \alpha(N-1)F(r^I)$$

In a sealed bid auction, transfers are $\tilde{t}_i(v) = r^I$ for all $v_i \geq r^I$ and $\tilde{t}_i(v) = 0$ for all $v_i < r^I$. Therefore, in order to obtain the expected transfers $E_{v_{-i}}\, t_i(v)$, the auctioneer has to set an entry fee $c^I = \alpha(N-1)F(r^I)$.

Corollary 2. The proof follows exactly the same lines. □

A3. Proof of Lemma 1 and Proposition 3.

Lemma 1. The first-best effort is the result of maximizing (12) under the constraint (IR). Since T enters negatively the objective function, (IR) binds and therefore $T = \psi(e)/\pi(e)$. Inserting this value, we can rewrite the objective function as $\tilde{W} = \pi(e)S(\lambda) - (1+\lambda)\psi(e)$. The first-best effort $e^\star(\lambda,\alpha)$ then satisfies:

$$\pi'(e^\star)S(\lambda) = (1+\lambda)\psi'(e^\star) \quad \Leftrightarrow \quad \frac{\psi'(e^\star)}{\pi'(e^\star)} = \frac{S(\lambda)}{(1+\lambda)} \tag{13}$$

Using (11), we have:

$$S'(\lambda) = \int_{r^R(\lambda)}^{\overline{v}} \sum_{i=1}^{N} \left[v_i - \alpha(N-1) - \frac{1-F(v_i)}{f(v_i)} \right] f(v)dv + \alpha(N-1)N$$

which, given (10) and Assumption 4(i), implies that $S'(\lambda) = R^R > 0$. Note also that:

$$\frac{d}{d\lambda}\left[\frac{S(\lambda)}{1+\lambda}\right] \propto (1+\lambda)S'(\lambda) - S(\lambda) = -\left[\int_{r^R(\lambda)}^{\overline{v}} \sum_{i=1}^{N} \frac{1-F(v_i)}{f(v_i)} f(v)dv - \alpha(N-1)N\right]$$

Therefore, given Assumption 4(ii), $\frac{d}{d\lambda}\left[\frac{S(\lambda)}{1+\lambda}\right] < 0$. As a result, and given (13), $\partial e^\star/\partial\lambda < 0$.

Last, $\lim_{\lambda\to+\infty} \frac{S(\lambda)}{1+\lambda} = \lim_{\lambda\to+\infty} S'(\lambda) = \lim_{\lambda\to+\infty} R^R = R^I$ since $\lim_{\lambda\to+\infty} r^R(\lambda) = r^I$. This means that as $\lambda \to +\infty$, the first-best effort $e^\star(\infty)$ solves:

$$\frac{\psi'(e^\star(\infty))}{\pi'(e^\star(\infty))} = R^I \quad \Leftrightarrow \quad e^\star(\infty) = e^I$$

Proposition 3. The regulator maximizes (12) under constraints (IR)-(MH). Let μ_1 and μ_2 be the multipliers for these constraints. The lagrangian is:

$$\pi(e)\Big[S(\lambda) - \lambda T\Big] - \psi(e) + \mu_1\Big[\pi'(e)T - \psi'(e)\Big] + \mu_2\Big[\pi(e)T - \psi(e)\Big]$$

The first-order conditions are:

$$\pi'(e)\Big[S(\lambda) - \lambda T\Big] - \psi'(e) = -\mu_1\Big[\pi''(e)T - \psi''(e)\Big] \tag{a}$$

$$-\lambda\pi(e) + \mu_1\pi'(e) + \mu_2\pi'(e) = 0 \tag{b}$$

If $\mu_2 > 0$ then the only solution compatible with (MH) is $e = 0$, so $\mu_2 = 0$. When $\mu_2 = 0$, then by (b) we have $\mu_1 = \lambda\pi(e)/\pi'(e)$ and the expected transfer received by the innovator is $T = \psi'(e)/\pi'(e)$. Let $g(e) = -\frac{\pi(e)}{\pi'(e)}[\pi''(e)\frac{\psi'(e)}{\pi'(e)} - \psi''(e)]$. Note that, given Assumption 1, $g(e) > 0$ for all e. Substituting T and μ_1 for their values, we can rewrite (a) as:

$$\pi'(e)S(\lambda) - (1+\lambda)\psi'(e) - \lambda\, g(e) = 0 \qquad \text{(a}'\text{)}$$

Differentiating (a′) with respect to λ, we get:

$$\frac{\partial e^R}{\partial\lambda}\Big[\pi''(e^R)S(\lambda) - (1+\lambda)\psi''(e^R) - \lambda\, g'(e^R)\Big] + \pi'(e^R)S'(\lambda) - \psi'(e^R) - g(e^R) = 0$$

Given $\pi''' \leq 0$ and $\psi''' \geq 0$, we have $g'(e) \geq 0$. Moreover:

$$\pi'(e^R)S'(\lambda) - \psi'(e^R) - g(e^R) =$$

$$-\tfrac{\pi'(e^R)}{1+\lambda}\left[\int_{r^R}^{\overline{v}}\sum_{i=1}^{N}\tfrac{1-F(v_i)}{f(v_i)}f(v)dv - \alpha(N-1)N\right] - \tfrac{g(e^R)}{1+\lambda} < 0$$

given Assumption 4(ii). Consequently, $\partial e^R(\lambda)/\partial\lambda < 0$. Also, (a′) can be rewritten as:

$$\frac{S(\lambda)}{1+\lambda} = \frac{\psi'(e^R(\lambda))}{\pi'(e^R(\lambda))} + \frac{\lambda}{1+\lambda}\frac{g(e^R(\lambda))}{\pi'(e^R(\lambda))}$$

Since $\lim_{\lambda\to+\infty}\frac{S(\lambda)}{1+\lambda} = R^I$, we have:

$$R^I - \frac{g(e^R(\infty))}{\pi'(e^R(\infty))} = \frac{\psi'(e^R(\infty))}{\pi'(e^R(\infty))} < R^I \quad\Leftrightarrow\quad e^R(\infty) < e^I$$

Last, $T^R(\lambda) = \frac{\psi'(e^R(\lambda))}{\pi'(e^R(\lambda))}$ which is decreasing in λ given that $\partial e^R/\partial\lambda < 0$. □

A4. Proof of Proposition 4.

Let $s^R(\lambda) = T^R(\lambda) - R^R(\lambda)$. Given $\partial T^R/\partial\lambda < 0$ and $\partial R^R/\partial\lambda > 0$, we have $\partial s^R/\partial\lambda < 0$. Note from (a′) that $T^R(0) = \frac{\psi'(e^R(0))}{\pi'(e^R(0))} = S(0)$. Hence:

$$s^R(0) = S(0) - R^R(0) = \int_{\alpha(N-1)}^{\overline{v}}\sum_{i=1}^{N}\frac{1-F(v_i)}{f(v_i)}f(v)dv - \alpha(N-1)N$$

so $s^R(0) > 0$ by Assumption 4(ii). Also, using the proof of Proposition 3, we have:

$$\lim_{\lambda\to+\infty} s^R(\lambda) = \frac{\psi'(e^R(\infty))}{\pi'(e^R(\infty))} - R^I = -\frac{g(e^R(\infty))}{\pi'(e^R(\infty))} < 0$$

By continuity, there exists a unique $\overline{\lambda}$ such that $s^R(\lambda) \gtreqless 0$ if and only if $\lambda \lesseqgtr \overline{\lambda}$.
□

A5. Proof of Corollary 3.

In equilibrium, and using (12) and Proposition 3, we have that welfare is:

$$\tilde{W}(e^R(\lambda), r^R(\lambda)) = \pi(e^R(\lambda))S(\lambda) - \psi(e^R(\lambda)) - \lambda\pi(e^R(\lambda))\frac{\psi'(e^R(\lambda))}{\pi'(e^R(\lambda))}$$

Using the envelope theorem: $\frac{\partial\tilde{W}}{\partial\lambda} = \pi(e^R(\lambda))S'(\lambda) = \pi(e^R(\lambda))R^R(\lambda) > 0.$

Since $e^R(0) = e^\star(0)$ then, by definition, $\tilde{W}(e^R(0), r^R(0)) > \tilde{W}(e^I, r^R(0))$. Furthermore,

$$\tilde{W}(e^I, r^R(0)) - \tilde{W}(e^I, r^I) =$$
$$\pi(e^I)\left[\int_{r^R(0)}^{\overline{v}} \sum_{i=1}^{N}\Big(v_i - \alpha(N-1)\Big)f(v)dv - \int_{r^I}^{\overline{v}} \sum_{i=1}^{N}\Big(v_i - \alpha(N-1)\Big)f(v)dv\right] - \psi(e^I) > 0$$

given $r^R(0) = \alpha(N-1) < r^I$. Therefore, $\tilde{W}(e^R(0), r^R(0)) > \tilde{W}^I(e^I, r^I)$. Given $\partial\tilde{W}/\partial\lambda > 0$, the inequality holds for any λ. □

A6. Proof of Proposition 5.

In the proof of Proposition 3 we have shown that $e^R(0) > e^I$, $\partial e^R/\partial\lambda < 0$ and $e^R(\infty) < e^I$. Hence, by continuity, there exists a unique value $\hat{\lambda}$ such that $e^R(\hat{\lambda}) = e^I$.

As for the relation between $\hat{\lambda}$ and $\overline{\lambda}$, recall that $\overline{\lambda}$ is defined as the value such that $s^R(\overline{\lambda}) = 0$, which implies that $T^R(\overline{\lambda}) = R^R(\overline{\lambda})$. Hence,we have:

$$\frac{\psi'(e^R(\overline{\lambda}))}{\pi'(e^R(\overline{\lambda}))} = R^R(\overline{\lambda}) \quad \text{and} \quad \frac{\psi'(e^R(\hat{\lambda}))}{\pi'(e^R(\hat{\lambda}))} = R^I$$

Since $R^R(\overline{\lambda}) < R^I$, the optimal effort is $e^R(\overline{\lambda}) < e^R(\hat{\lambda})$. Consequently, $\overline{\lambda} > \hat{\lambda}$.
□

A7. Proof of Proposition 6.

Part(i) is immediate given the definition of x^R, x^I and that $r^R < r^I$ for all λ and α. As for part(ii), we know that $\partial e^R/\partial\lambda < 0$ and $\partial r^R/\partial\lambda > 0$, which implies that $\partial x^R/\partial\lambda < 0$ and $\partial[\pi(e^R)x^R]/\partial\lambda < 0$. Since $e^R(0) = e^\star(0) > e^I$, we have that $\pi(e^R(0))x^R(0) > \pi(e^I)x^I$. Also, $e^R(\infty) < e^I$ and $r^R(\infty) = r^I$ imply that $\pi(e^R(\infty))x^R(\infty) < \pi(e^I)x^I$. The threshold $\tilde{\lambda}$ is obtained by continuity. $\square$

A8. Proof of Proposition 7.

For any reserve price $r \neq r^I$, we have $R^R(r) < R^I$. Now, given that $\hat{e} = \arg\max_e \pi(e)R^R(r) - \psi(e)$ and $e^I = \arg\max_e \pi(e)R^I - \psi(e)$, it is immediate that $\hat{e} < e^I$. Furthermore, for all $r \gtreqless r^I$, $\partial R^R(r)/\partial r \lesseqgtr 0$, so $\partial\hat{e}/\partial r \lesseqgtr 0$. Also, by differentiating the condition that determines the optimal effort we can easily check that $\partial^2\hat{e}/\partial r^2 < 0$. In the absence of transfers and for a given reserve price r, we can rewrite the welfare of the industry as:

$$\hat{W}(r) = \pi(\hat{e}(r))\Big[U(r) + R(r)\Big] - \psi(\hat{e}(r))$$

where $U(r)$ is the producers' surplus, $R(r)$ the revenue of the auction and

$$U(r) + R(r) = \int_r^{\overline{v}} \sum_{i=1}^{N} X_i(v)\Big[v_i - \alpha(N-1)\Big]f(v)dv$$

The optimal reserve price is solution of:

$$U(r)\pi'(\hat{e}(r))\frac{d\hat{e}}{dr} + \pi(\hat{e}(r))\Big[U'(r) + R'(r)\Big] = 0$$

Let r_0 be the solution of $U'(r) + R'(r) = 0$. It comes immediately that $r_0 = r^R(0) < r^I$. Besides, $V'(r) + R'(r) \lesseqgtr 0$ for all $r \gtreqless r_0$. Given that $\partial\hat{e}/\partial r \lesseqgtr 0$ for all $r \gtreqless r^I$, the optimal reserve price is such that $r \in (r_0, r^I)$. Using the fact that $\partial^2\hat{e}/\partial r^2 < 0$, it can be easily checked that the welfare is concave in r. Moreover, $\hat{W}'(r_0) > 0$ and $\hat{W}'(r^I) < 0$, which proves the result. $\square$

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