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JEL Classification: D8, H57, O31, O38, L2

Keywords: Crowding out, innovation policy, Procurement, Research and Development, Steering effect

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Innovation Policy: Procurement vs Grants*

Alessandro De Chiara† and Elisabetta Iossa‡

10 October, 2019

Abstract

We develop a model of funding competition to compare two alternative and widely used approaches: (i) a (demand-side) procurement approach, in which the public authority specifies the type of project it will finance and (ii) a (supply-side) grant system, in which any type of project can be financed. The public authority can verify the characteristics of the projects submitted, but does not know which other projects are available. The paper sheds light on the role of public procurement to foster innovation, by directing inventions.

JEL Classification: D8, H57, L2, O31, O38.
Keywords: Crowding out, Grants system, Innovation Policy, Procurement, Research and Development, Steering effect.

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1 Introduction

Innovation policies can be broadly classified as supply-side oriented or demand-side oriented. Supply-side policies seek to incentivize the production of innovation by assisting companies with funding for their R&D investment. Government grants for research projects are a traditional supply-side instrument. Demand-side policies seek to foster innovation by boosting its demand. Using public procurement to stimulate innovation is a demand-side policy. Policy interest towards public procurement as an innovation policy instrument is growing worldwide.[1]

Public procurement played a major role in stimulating innovation in the 50's and 60's, when public needs, mainly in the defence industry, made the US government heavily involved as user-demander of technologies. The projects that were financed produced significant commercial spillovers and influenced the entry and growth of highly innovative firms.[2] Today, public procurement accounts for around 12% of GDP in OECD countries (World Bank, 2017) and its role as innovation policy instrument remains considerable. However, whether this justifies an approach where the government "picks winners" by supporting specific technologies is controversial: lack of information may limit governments' ability to guide technological development.[3]

Supply-side policies also have drawbacks. R&D grants and subsidy programs may crowd out private investment, inducing firms to substitute private funds with public ones, and misallocate resources if firms invest in profitable technologies rather than socially valuable ones.[4]

In this paper, we investigate the role of public procurement of innovation. We study whether public procurement should be used as an innovation policy instrument, that is, irrespective of whether there is a concrete public need for a certain innovation, and when it should be used instead of alternative instruments, such as research grants or subsidies. These issues are quantitatively relevant: the US government alone invests more than $50 billion per year

[1] See Aho Group Report (Aho et al. 2006) and OECD (2011, 2014).

[2] The origins of the Internet date back to research commissioned by the US government in the 1960s to build communication via computer networks; the development of the iRobot PackBot stemmed from research commissioned by the US Advanced Research Development Agency (DARPA) to develop robots that could walk autonomously, and the basis for personal computers was set by the US supercomputing procurement program which led to the development of the first processor on a chip (Ramboll Management, 2008; and Kira and Maurery 2013). Public Procurement also played a major role in fostering innovation more recently, by shifting civil procurement towards high-tech products stimulating the IT revolution in the 70s and 80s (Cozzi and Impulliti, 2010).

[3] See Nelson and Langlois (1983).

[4] See e.g. Lerner, (2009) for a discussion.

in R&D procurement and about the same amount in research grants; these amounts represent about two-thirds of all total federal spending in R&D.

The starting point of our analysis is the observation that procurement and grants differ markedly in terms of decision making on project choice. In the former, the government guides technological development by financing specific projects or areas, whereas in the latter the unconditionality of funds gives firms more discretion over their technological investment.[5] This distinction is key when firms are unable to pursue all projects due to capacity constraints, and thus the availability of public funds may induce a change in the direction of their investment.

To study these issues, we consider an economy in which a public authority runs a research tournament to finance one project. There are two different types of (innovative) projects: socially desirable (type A) and privately desirable (B). Firms randomly draw one project or both. The public authority cannot influence the firm's submission strategy by outcome-contingent rewards but it can choose to specify which type of project will be financed. A procurement policy finances the implementation cost of a project of type A. A grant covers the the implementation cost of either a project of type A or of type B, with a preference for A. The government is informed about the benefit and the type of project submitted but cannot see which other projects are available to the firms. For the main part of the paper it is assumed that the firms are willing to self-finance privately desirable projects (type B) whereas socially-desirable projects are only pursued with public funds. Due to capacity constraints, firms can only pursue one project (even if they draw both). The cost of developing a project is the same for all projects, and it is larger when public funds are used to support it.

We model the firm's decision of which project to submit. The strategic 'action' comes from agents who draw both projects. We show that a firm with both projects available submits A if and only if the funding is sufficiently high, relative to the private benefits that B generates. The threshold is greater under a grant, because of the opportunity cost of getting the B project founded instead.

In the scenario where firms behave identically in equilibrium and an A project is financed, the innovation policy helps to finance projects which the firms would not have financed with their own money. This is what we call the *investment effect.* The only difference between grants and procurement then occurs in the states of the world in which everyone can and also want to

[5] An example of public procurement of innovation is the U.S. procurement of supercomputers. An example of unconditional research grants is the European Research Council (E.R.C.) funding program.

submit B projects only. In that scenario, a grant funds a B project whereas procurement does not. Because of the cost of public funds, this is socially inefficient, making a grant less desirable. This is the *crowding-out effect.* However, in the scenario where under a grant system every firm drawing both projects submits B whereas firms under procurement submit A, the benefits from avoiding the *crowding-out effect* still exist, but now there is also a loss: it becomes more likely that a firm drawing both A and B projects may win under procurement to do an A project. If there are firms obtaining only A projects, this is a loss for society. As project A would have been done by a firm obtaining only A and the firm obtaining A and B does not invest B. This is the *steering effect.* Which policy dominates in this case depends on the parameter configuration. We find that the beneficial impact of public procurement is maximal when public needs are large or the cost of public funds is large.

The results that we obtain rationalize the use of public procurement to spur innovation by emphasizing its catalytic role, allowing the creation of new markets whilst minimizing crowding out, but they warn that procurement of innovation must be justified by real public sector needs. In line with our predictions, the US innovation procurement that took place in the 50's and 60's was driven by specific public sector needs rather than a general desire to boost innovation (Malerba et al., 2008 and Mowery, 2012). Furthermore, the US Code, which explicitly regulates the choice between procurement and grants, specifies that US federal agencies should use procurement contracts when they seek to acquire products or services for their own benefit; grants should instead be preferred when an agency seeks to support a public purpose (31 U.S.C. § 6301-04). Similarly, Europe calls to enlarge the scope for procurement of innovation, but the dedicated funds for innovation procurement in Horizon 2020 target specifically ICT, health, security and energy, where public sector needs are greatest.

We extend the model in different directions. First, we compare the two policies when projects are so large in size that also privately desirable projects (type B) would not be pursued without public funds. In this case, crowding out is not a problem and instead it is valuable to finance also projects of type B. Second, we consider the case of aligned preferences in which the socially valuable projects are also the most profitable ones. In both cases, the grant system now brings the additional benefit of using the firms' superior information to finance valuable projects when no better project is available. Third, we study the effect of these policies on effort in basic research and in applied research. Both policies foster R&D investment but procurement also changes its direction. In particular, by giving more discretion to the firm, the grant system enhances the expected returns from a breakthrough, strengthening incentives for effort in basic research. The grant system also strengthens applied research towards privately profitable innovation. Instead, public procurement redirects investment towards socially valuable innovation.

The rest of the paper proceeds as follows. In section 2 we review the related literature. In section 3 we describe the set-up of the baseline model. In section 4 we study project choice under grants and procurement systems. In section 5, we discuss some crucial ingredients of our analysis. In section 6, we consider a number of extensions, including incentives for R&D (section 6.1), the case of large projects (section 6.2) and of aligned preferences (section 6.3). In section 7 we provide some concluding remarks, testable predictions and policy implications.

2 Related Literature

Our paper provides a contribution to three strands of literature: public procurement of innovation, the direction of innovation and delegation.

Public Procurement of Innovation. The potential role of public procurement in boosting the demand for innovative products was first highlighted by Geroski (1990), Edquist and Hommen (2000), Maurer and Scotchmer (2004) and Edler and Georghiou (2007). These papers conceptually justify public procurement as a technology pull policy which can help to implement socially valuable projects.[6] We enrich this discussion by building a formal model of procurement of innovation, which allows us to identify investment, crowding out and steering effects and to compare procurement vs grants. To the best of our knowledge, the steering effect that we highlight is novel. We are also not aware of other papers that have shown that crowding out is stronger with grants rather than procurement and that procurement of innovation is preferable for fostering applied research effort rather than basic research. The trade-off among these effects in determining the best innovation policy is the chief contributions of our model.

[6] The empirical evidence on the effect of public procurement of innovation is rather scant and mostly limited to case studies (see e.g. Lichtenberg, 1988), with few exceptions using innovation surveys (e.g., Aschhoff and Sofka, 2009, and Guerzoni and Raitieri, 2015). The interest in procurement of innovation is however growing, both at the theoretical level, see for example Che et al. (2017) on the design of the procurement mechanism, and at the empirical level. Recent studies analyze the impact of private procurement on business (Howell, 2017), private R&D (Slavtchev and Wiederhold, 2017), and the role of critical factors such as the number of firms competing (Bhattacharya, 2018) and the competence of public buyers (Bruce *et al.* , 2018, and Decarolis *et al.*, 2019)

Direction of innovation. A recent literature has started to investigate the market distortions linked to the direction of innovation rather than the quantity of R&D and the policy remedies to mitigate it.[7] In Hopenhayn and Squintani (2017), competitive markets allocate excessive resources to some high-value research areas, due to cannibalization of returns from competing innovators and imperfect property rights. Spreading grants across different research lines is welfare improving. In Bryan and Lemus (2017) innovators may overlook how their inventive effort today affects the set of projects that will be available in the future, leading to misallocation of effort across projects. Policies like prizes and patents may generate their own distortions, as they fail to condition funds on the inventions that are not developed in equilibrium. Compared to this literature, we consider a static rather than a dynamic setting and we focus on grants vs procurements, emphasizing the distortions that the steering effect generates when funding cannot be conditioned on the set of available projects.

Delegation. Since Holmstrom (1984), a vast literature has characterized the optimal delegation decision in a principal-agent setting when projects are always feasible and the agent has, or can acquire, private information about a payoff-relevant state of the world. In our model, we follow Armstrong and Vickers (2010) in positing a different form of asymmetric information. Projects' payoffs are known, but only a finite collection of projects is feasible and only the agent knows what those projects are. Berkovitch and Israel (2004) study a direct mechanism specifying project implementation probabilities and monetary transfers as function of reported project availability. Compared to these papers, we introduce multiple agents and study project submission strategies under competition. We also introduce self-financing of projects, to analyze steering and crowding out effects.

3 Baseline Model

There are n homogeneous firms competing for public funds to implement a project. The public authority commits to finance at most one project. Projects differ in the social returns they generate and in their profitability. All parties are risk-neutral.

Projects and states. Projects are random variables and can be of two types,

[7] The rationale for innovation policy was provided by several models developed in the 50' and 60's showing that the nature of knowledge as a public good, or the uncertainty of the innovation process, result in an underinvestment that hampers productivity and growth (see e.g. Nelson, 1959, and Arrow, 1962).

A or B. Draws are statistically independent among firms. Each firm can be in one of three states: $i = A, B, AB$, depending on whether it has only a type A project, only a type B, or both types, A and B. The probability of each of these states is denoted by P_i, with $P_i \geq 0$ and $\Sigma P_i = 1$. Implementing a project costs $k \geq 0$, if privately financed and $(1 + \lambda)k$ if publicly financed, where $\lambda > 0$ captures the shadow cost of public funds. Firms have capacity constraints which limit the number of projects they can pursue at a time without incurring in a significant cost increase. In particular, we assume that each firm can pursue at most one project at a time.[8] The number of potential projects available to each firm is exogenous.[9]

Preferences. The public authority maximizes consumer surplus and the firms maximize profits, all net of financing cost. Project A yields u^H to the public authority (we can indifferently think of u^H as a social externality or consumer surplus) and generates profits μ^L to a firm. Project B yields $u^L < u^H$ to the public authority but higher profits $\mu^H > \mu^L$ with $\Delta_u \equiv u^H - u^L$ and $\Delta_\mu \equiv \mu^H - \mu^L$ and $\Delta_u > \Delta_\mu$. Thus, the preferences of the public authority and of the firms are conflicting: the public authority prefers project A whilst the firms prefer project B.[10] We consider the alternative case of aligned preferences in Section 6.3. For the main part of the analysis, we simplify and set $u^L = 0$. Furthermore, we assume that a firm is willing to privately finance a B project but not an A project:

$$\mu^L > k > \mu^L, \tag{A1}$$

which allows us to model crowding out.[11]

Economic welfare is given by the sum of consumer surplus and firms' profits, net of the cost of implementing a project. As $\Delta_u > \Delta_\mu$ the socially optimal project is of type A. The interests of the public authority are therefore aligned with those of the wider society.[12]

[8] Capacity constraints are well documented in procurement (see, for example, Jofre-Bonet and Pesendorfer, 2003). We come back to this assumption in Section 5.

[9] We relax this last assumption in Section 6.1.

[10] For example, A is a project on automated traffic system and B is a project on automated video surveillance. A firm specialized in automatization may be able to pursue either of them. However, A has greater user value to the public authority than B but B generates higher private returns.

[11] In Section 6.2, we consider the alternative case of large projects where $k > \mu^H$.

[12] The perspective of the public authority is the one of a user of a technology, which enjoys the level of consumer surplus associated with the project it buys. The welfare perspective is the one of a government, which enjoys a total value that is given by the sum of the consumer surplus and industry profit, net of financing cost.

Financing policies. The financing policy takes the form of a research tournament with a fixed prize k.[13] Each firm submits at most one project to the public authority. We compare two variants of the financing policy:

- *Procurement*: The public authority announces that only a type A project will be financed. Ties among firms submitting A are broken randomly.
- *Grant system*: The public authority announces that it is willing to finance either A or B, with a preference for A. Ties among firms submitting A, or ties among firms submitting B when no firm has submitted A, are broken randomly.

We determine under what conditions each option is preferred from a social standpoint.

Information. The number n of competing firms, the probability distribution P_A, P_B, P_{AB}, and the preferences of all players are common knowledge. As in Armstrong and Vickers (2010), the public authority can verify the projects submitted by the firms, knows their payoffs but only the firm knows which types of projects it has available.[14] Monetary incentives cannot be used to induce the submission of a certain type of project.[15]

Timing. The baseline game unfolds as follows.

- *Policy decision stage.* In stage 0, the public authority decides the financing policy.
- *Submission stage.* In stage 1, having observed its available projects, each firm non-cooperatively and simultaneously decides which project to submit.
- *Implementation Stage.* In stage 2, the public authority observes the projects submitted and chooses which project to finance, if any. The

[13] Compared to the standard research tournament (Taylor, 1995), in which firms compete for a fixed prize on the same type of project and invest to improve the quality of their innovation, we model a project competition in which firms must decide which project to submit.

[14] An example is the submission of research projects to the a grant institution. Project submission requires a detailed description of the aim and scope of the research and the methodology used. Evaluators can assess this information competently but cannot observe which other project the researcher could have submitted.

[15] We discuss the implications of relaxing this assumption in Section 5.

firm that has won the contest implements the winning project using public funds. The other firms decide whether and which project to implement with their own funds.

Equilibrium concept. The contest described above gives rise to a three-stage game of imperfect information with n players. In the submission game, we focus on symmetric (Pareto efficient) Bayesian-Nash equilibria in pure strategies.

Market option. When there is no policy intervention, no firm pursues a project of type A, whilst all the firms that are not in state (A) pursue a B project with their own funds. Therefore, social welfare is:

$$W^0 = n(1 - P_A)(\mu^H - k),$$

where $n(1 - P_A)$ is the total number of projects pursued.[16]

4 Submission game

In this section we analyze the firms' project submission strategy and implementation decision under a procurement and a grant system.

4.1 Grant system

Under a grant system, the submission strategy and implementation decision depend on which of the following contingencies arises.

- State (AB): When a firm has both projects of type A and of type B, it obtains μ^L if it submits A and wins, and μ^H if it submits B and wins. In both cases, if it does not win, the firm implements B with its own funds and obtains $\mu^H - k$. Therefore, the firm submits A or B depending on the difference between k and Δ_μ and on the strategies of the rivals, which determine the probability of winning.
- State (A): When a firm only has a project of type A, it submits A and, as $\mu^L < k$, it implements A if and only if it wins the contest.

[16] It is derived by applying the formula for the expected value of a binomial distribution:

$$\sum_{j=1}^{n} j \binom{n}{j} (1 - P_A)^j (P_A)^{n-j} = n(1 - P_A).$$

- State (B): When a firm only has a project of type B, it submits B and, as $\mu^H > k$, it implements B with public funds if it wins the contest and with its own funds if it does not win.

Denote by σ_A (resp. σ_B) the strategy where a firm submits A (resp. B) in state (AB). In the light of the above considerations, restricting attention to symmetric pure strategies, there are two candidate equilibria:

- Each firm submits A in states (A) and (AB), and B in state (B). We denote this candidate equilibrium by $Eq^{Gr}(\sigma_A)$.
- Each firm submits A in state (A), and B in states (B) and (AB). We denote this candidate equilibrium by $Eq^{Gr}(\sigma_B)$.

The critical decision stage is (AB). Winning with a project of type A yields μ^L with an opportunity cost of $\mu^H - k$ from relinquishing to implement the most profitable project. The differential benefit is $k - \Delta_\mu$. Winning with a project of type B yields instead a net benefit of k, the prize granted under the funding policy. With a little abuse of terminology, we denote the *value of the funding policy* in this state as:

$$v \equiv \frac{k - \Delta_\mu}{k}.$$

It is then immediate that for $v < 0$, the only equilibrium is $Eq^{Gr}(\sigma_B)$, as a firm prefers to undertake B with its own funds rather than obtain k to implement A. Instead, if $v \geq 0$, whether a firm in (AB) submits A or B depends on its expectations as to the probability of winning the contest in each case.

Denote by $\gamma_k(\sigma_j)$ the probability of winning the contest by submitting project $k = A, B$ when all the other firms submit project $j = A, B$ in state (AB). In state (AB), the firm obtains $\mu^H - k$ if it does not win, as it implements B with its own funds; if it submits A and wins it obtains μ^L. Therefore, its expected profit from submitting A is:

$$\pi_{AB}^{Gr}(\sigma_A; \sigma_j) = \mu^H - k + \gamma_A(\sigma_j)(k - \Delta_\mu), \text{ for } j = A, B. \tag{1}$$

By contrast, if a firm submits B in state (AB), it implements B irrespective of whether it receives funds from the public authority, but it will obtain k from the public authority if it wins. Therefore, firm i's expected profit from submitting B in state (AB) is:

$$\pi_{AB}^{Gr}(\sigma_B; \sigma_j) = \mu^H - k + \gamma_B(\sigma_j)\, k, \text{ for } j = A, B. \tag{2}$$

It follows that σ_j $(j = A, B)$ is a (symmetric) Bayesian-Nash equilibrium if:

$$\pi_{AB}^{Gr}(\sigma_j; \sigma_j) \geq \pi_{AB}^{Gr}(\sigma_k; \sigma_j) \text{ for } j \neq k.$$

The probability of winning the contest depends on the other firms' equilibrium strategy and it is given by:[17]

$$\begin{aligned}
\gamma_A(\sigma_j) &= \sum_{\alpha=0}^{n-1} \frac{1}{n+1} \binom{n-1}{n} x_j^n (1-x_j)^{n-1-\alpha}, \\
&= \frac{1-(1-x_j)^n}{nx_j}, \\
&= \gamma_B(\sigma_j) + \frac{1-(1-x_j)^{n-1}}{nx_j} > \gamma_B(\sigma_j), \\
\gamma_B(\sigma_j) &= \frac{(1-x_j)^n}{n(1-x_j)} = \frac{(1-x_j)^{n-1}}{n}.
\end{aligned}$$

with $x_A = 1 - P_B$ and $x_B = P_A$; for $j = A, B$, and where nx_j is the number of projects A submitted under σ_j.

Note that $\gamma_A(\sigma_j) > \gamma_B(\sigma_j)$. Intuitively, the probability of winning is greater when A is submitted as: (i) by submitting B, a firm wins with probability $1/n$ if all the rivals have submitted B, and with probability zero, otherwise. By submitting A, a firm wins with probability 1 if all the rivals have submitted B, and with probability greater than zero, otherwise. Thus, there exists a trade-off: submitting A in state (AB) is associated with a greater probability of winning but a lower profit conditional on winning. The following lemma then shows that $Eq^{Gr}(\sigma_A)$ and $Eq^{Gr}(\sigma_B)$ are equilibria of the game, depending on the terms of this trade-off.

Lemma 1 *Under a grant system, there exists a unique symmetric Pareto-efficient Bayesian Nash equilibrium characterized as follows:*
(i) If:

$$v > \hat{v} \equiv \frac{\gamma_B(\sigma_B)}{\gamma_A(\sigma_B)},$$

competing firms play $Eq^{Gr}(\sigma_A)$*;*
(ii) If $v \leq \hat{v}$*, competing firms play* $Eq^{Gr}(\sigma_B)$*.*
(iii) Equilibrium $Eq^{Gr}(\sigma_A)$ *becomes more likely when competition increases:* $\hat{v}$ *decreases with* n*.*

[17]To understand this expression, suppose that the equilibrium is $S(\sigma_A)$ and there are exactly three rival firms which have a project of type A. The probability of winning is $\frac{1}{4}$, which must be multiplied by the probability of having exactly three rivals, that is: $\binom{M-1}{3}(1-P_B)^3 P_B^{M-4}$.

Proof: in the Appendix.

The availability of public funds may change the firm's choice of which project to implement, from B to A. We call this effect "*steering effect*". By submitting A, the firm increases the chance of winning, but it enjoys lower profits if it wins. The firm will therefore submit A when the reward from winning is high compared to the loss from not implementing the most profitable project, i.e. if the policy value v is high. Vice versa, it will submit B when the policy value is low. Furthermore, the incentives of firms from steering their investment towards the public authority's favorite project increase with the level of competition. As the number of firms rises, the likelihood that at least one firm will be in state (A) (and thus submit A) increases, and thus the probability of winning by submitting B decreases.

4.2 Procurement

Suppose that the public authority uses a procurement system. Now, submitting B is not an option, as B will never be financed. Therefore, we can identify two (symmetric) pure strategy Bayesian-Nash equilibria.

- *Equilibrium* $Eq^{Pr}(\sigma_A)$. Each firm submits A in states (A) and (AB). In states (B) and (AB) if it does not win the contest, each firm implements B with its own funds.

- *Equilibrium* $Eq^{Pr}(\sigma_B)$. Each firm submits A in state (A). In states (B) and (AB), each firm implements B with its own funds.

The following lemma summarizes the equilibrium conditions.

Lemma 2 *Under a procurement system, there exists a unique symmetric Pareto efficient Bayesian Nash equilibrium characterized as follows:*
(i) If $v > 0$, *competing firms play* $Eq^{Pr}(\sigma_A)$;
(ii) If $v \leq 0$, *competing firms play* $Eq^{Pr}(\sigma_B)$.

As under a grant system, the firm's submission strategy in state (AB) depends on v. Notably, under procurement, the steering effect occurs more frequently in equilibrium: whenever $v > 0$ rather than $v > \hat{v}$. By restricting the firm's project choice, the public authority obtains that socially useful projects are submitted more often.

4.3 Comparison

From the equilibrium characterization developed in the previous sections, we can identify three relevant scenarios:
(i) $v \geq \hat{v}$: the equilibria are $Eq^{Gr}(\sigma_A)$ and $Eq^{Pr}(\sigma_A)$. The steering effect occurs under both under a grant system and under procurement.
(ii) $v \in (0, \hat{v})$: the equilibria are $Eq^{Pr}(\sigma_A)$ and $Eq^{Gr}(\sigma_B)$. The steering effect occurs only under procurement.
(iii) $v \leq 0$: the equilibria are $Eq^{Gr}(\sigma_B)$ and $Eq^{Pr}(\sigma_B)$. The steering effect does not occur in either case.

Comparing expected welfare in each of these three areas, the following proposition is then obtained:

Proposition 1 *(Procurement vs grants) With conflicting preferences, the procurement system maximizes welfare for values of* $v \notin (0, \hat{v})$. *When* $v \in (0, \hat{v})$, *the procurement system is preferable for welfare only for large and costly public funds (*λ *high) or when the public authority's preferred project yields relatively large social benefits (*$\Delta_u - \Delta_\mu$ *high).*

Proof: in the Appendix.

Compared to non-intervention, both procurement and grant systems bring the benefit of an *investment effect*: the additional project implementation compared to the market option, which occurs when the winning firm is in state (A). However, the grant system suffers from the *crowding-out effect*: the winning firm substitutes private funds with public funds to finance project B. This effect always harms the public authority and it is also welfare reducing, due to the shadow cost of public funds. The crowding-out effect per sè implies that the procurement system will always be preferred to the grant system whenever the behavior of the firms in state (AB) is the same, as when $v \leq 0$, where the steering effect is absent, or when $v \geq \hat{v}$, where the steering effect is present under both the the grant system and procurement.

Instead, when $v \in (0, \hat{v})$, where the steering effect occurs only under the procurement system, there is a trade-off: a procurement system does not suffer from crowding out and it leads to project A being implemented more often than when firms follow strategy σ_B under a grant system. However, total profits are now lower because a firm in state (A) may lose against a firm in (AB), in which case fewer projects are implemented than when the winning firm is in (A). This is the downside of the steering effect. This suggests that the procurement system is most desirable when the cost of crowding out is high (λ is high), so that avoiding crowding out is especially valuable, or the welfare gain from replacing B with A is large ($\Delta_u - \Delta_\mu$ high), so that the benefits of steering sufficiently outweigh its costs.

These insights offer a rationale to the concern that, as an innovation policy, procurement may not be very effective if it is not dictated by real public needs, a result in line with the warnings first made by Nelson and Langlois (1983). In fact, our equilibrium analysis suggests that, if public needs are present ($\Delta_u > 0$), the direct impact of the steering effect can never be negative in equilibrium:

$$\Delta_u - \Delta_\mu - \lambda k > 0. \tag{3}$$

This is because Δ_u must be greater than $(1 + \lambda)k$ as otherwise the public authority would be better off getting a project of type B off the market rather than hoping to get A at price $(1 + \lambda)k$ via the founding competition; and k must be greater than Δ_μ as otherwise the firm would prefer to pursue B rather than steer its investment towards A. However, when the externality caused by a firm in state (AB) displacing a firm in state (A) is factored in, it may well be the case that the equilibrium without steering under a grant system dominates the procurement equilibrium with steering.

5 Discussion

We discuss below some crucial ingredients of our analysis and side results.

Capacity Constraint. The capacity constraints of firms is a necessary condition for the downside of the steering effect to arise. If a firm in (AB) could implement both projects, it would always choose to submit project A, as it is associated with a greater probability of winning ($\gamma_A(\sigma_i) > \gamma_B(\sigma_i)$) for $i = A, B$), and then carry out project B with its own funds. Procurement would then always be the preferred policy. If capacity constraints were moderate, in the sense that the firm could implement a second project only at cost $k' > k$, then the steering effect (implementing A instead of AB) would continue to arise if the firms' payoff from implementing A with public funds and B with own funds were smaller than the payoff from implementing A only, that is: $\mu^L > k'$. Having a firm in (AB) winning the contest rather than a firm in (A) would then still lead to a welfare loss of $k' - k$, albeit smaller than $\mu^L - k'$.

Choice of procurement. The analysis has been carried out by comparing procurement vs grants from a welfare perspective. A natural question to ask is whether the incentives of the public authority to choose public procurement are aligned with those of society. It is possible to show that in our setting a public authority would choose the procurement option too often.

The intuition follows from the fact that the public authority does not internalize the negative impact of the steering effect on the firms' profits. Therefore, when $v \notin (0, \hat{v})$, the interests of the public authority and of society as a whole are aligned: public procurement is chosen by the public authority and this is the best policy. Conversely, when $v \in (0, \hat{v})$, the public authority will choose procurement even if a grant system may be preferable.

Competition. We have shown that an increase in the number of firms raises the incentives to submit A under a grant system, whilst it has no effect on the submission strategy of the firm under a procurement system. We notice here that more competition increases the benefit of each policy, as it enhances the probability that an A project is available. However, how more competition affects the comparison procurement vs grants is ambiguous.

The intuition for such unclear outcome can be explained as follows. When $v \in (0, \hat{v})$ stronger competition increases the chances that the contest is won by a firm in state (A) under equilibrium $Eq^{Gr}(\sigma_B)$. This improves the relative merit of $Eq^{Gr}(\sigma_B)$ with respect to $Eq^{Pr}(\sigma_A)$, where instead there is no guarantee that the contest will be won by a firm in state (A). Other things equal, such effect favors a grant system. However, Lemma 1(iii) states that $\hat{v}$ is decreasing in n which implies that the range of values of v where the equilibrium under a grant system is $Eq^{Gr}(\sigma_B)$ decreases with n, and there is therefore a countervailing effect.

Size of subsidy. We have considered a financing policy in which the prize is equal to the cost of implementation. Raising the prize to some k' above k, would lead to an increase in the value of the financing policy from $\frac{k-\Delta_\mu}{k}$ to $\frac{k'-\Delta_\mu}{k'}$ and a strengthening of the incentives to choose a strategy σ_A under both procurement and grants.[18] Such policy however would not affect the choice of procurement versus grants. In fact, if the downside effect of steering were to yield $W^{Gr}(\sigma_B) > W^{Pr}(\sigma_A)$, then raising the prize would cost more without changing the strategy of the firms under procurement, as the equilibrium is already $Eq^{Pr}(\sigma_A)$, and under grants would lead to an equilibrium welfare lower than $W^{Gr}(\sigma_A)$ which is already dominated by $W^{Pr}(\sigma_A)$.

[18] This possibility is analyzed in De Chiara and Iossa (2019b) who study the optimal budget cap by research funding authorities.

6 Extensions

In this section we analyze a number of extensions, which allow us to provide insights on a number of cases that are relevant in practice. First, we endogenize the available projects by considering them as the result of a research investment (section 6). Second, we relax assumption (A1) so as to compare procurement vs grants for large projects (section 6.2. Third we consider the case in which the preferences of the public authority and the firm are aligned (section 6.3). The overall picture that emerges is that it is difficult to justify using public procurement as an innovation policy instrument unless there is a significant and concrete public need that the market alone would not address.

6.1 R&D effort

In this section we analyze incentives for R&D. We model the firm's research and development effort as a two-step process. First, the firm exerts effort to obtain a breakthrough, a new technology with potential for commercialization. This effort is denoted by e and it is interpreted as basic (or generic) research. It costs $e^2/2$ to the firm and gives a probability $e \in [0,1]$ that the breakthrough is obtained. If a breakthrough is obtained, the firm becomes able to implement either project A or B. For simplicity, we assume that $P_{AB} = 0$. Specifically, A becomes available with probability P_A and B with probability P_B.

Second, if a breakthrough is obtained, the firm can exert effort to further develop the technology so as to widen the set of potential applications. This effort is denoted by ρ and we interpret it as applied research.[19] It costs $\rho^2/2$ to the firm and gives a probability $\rho \in [0,1]$ that a new application is obtained. For instance, if the breakthrough has lead to the technology for a project of type A (respectively, B), the firm can exert effort to acquire the capability of undertaking also project B (resp., A).

To keep things simple, we focus on the incentives of an entrant (e.g., the n-th firm), which takes the equilibrium of the submission game as given when deciding its levels of basic effort (e) and applied research effort (ρ).

Let Π^J denote the firm's expected profit in case of a breakthrough under policy $J \in \{Gr,Pr\}$. We have:

$$\Pi^J(\sigma_h) = \sum_i P_i \left[\left(1-\rho_i^J\right)\pi_i^J(\sigma_h) + \rho_i^J \pi_{AB}^J(\sigma_h) - \frac{\left(\rho_i^J\right)^2}{2} \right],$$

[19] This distinction links our paper also to the to De Fraja (2016) who studies the optimal allocation of funding among basic and applied research.

where π_i^J denotes the (expected) profit of the firm in state $i = A, B$, and ρ_i^J denotes the applied research effort in state $i \in \{A, B\}$ under policy $J \in \{Gr, Pr\}$. The effort in basic research then solves:

$$e^J(\sigma_h) \equiv \arg\max_e e\Pi^J(\sigma_h) - \frac{e^2}{2},$$

which yields:

$$e^J(\sigma_h) \equiv \Pi^J(\sigma_h). \quad (4)$$

To guarantee an interior solution, i.e. $e < 1$, we assume that $\Pi^J(.) < 1$.

Effort in applied research in state i maximizes profit once a breakthrough is obtained. It solves:

$$\rho_i^J(\sigma_h) \equiv \arg\max_\rho [\left(1 - \rho_i^J\right) \pi_i^J(\sigma_h) + \rho_i^J \pi_{AB}^J(\sigma_h) - \frac{(\rho_i^J)^2}{2}].$$

This yields:

$$\rho_i^J(\sigma_h) \equiv \pi_{AB}^J(\sigma_h) - \pi_i^J(\sigma_h). \quad (5)$$

Both efforts depend on the innovation policy in place, $J \in \{Gr, Pr\}$, as well as the submission strategy followed by the firms, σ_h. In addition, effort in applied research is also a function of the type of project that the firm has obtained with the breakthrough, $i = A, B$. In particular, if the firm has obtained B, it will spend resources to avail itself also of project A, if an only if its submission strategy is σ_A, as otherwise obtaining A has no value to the firm. If the firm has obtained A with a breakthrough, it will spend resources to avail itself of project B, in order to implement it with its own money in case it does not win, and also to submit it if its strategy is σ_B and project B can be financed.

The following proposition compares the policies according to their effort incentives. In all cases, incentives will be weakly greater than under the market option, where obtaining A is not profitable.

Proposition 2 *(i) A grant system yields the greatest effort in basic research; (ii) A grant system also maximizes effort towards profitable applications. A procurement system maximizes effort towards socially valuable applications.*

Proof: see the Appendix.

Effort in basic research is greater when the expected profits from a breakthrough are higher. Using a grant system then best motivates this effort, as expected profits are greater when the firm has more discretion. The incentive to exert effort in applied research instead hinges on the gain that the firm obtains from seeking a different type of project that the one it can already do. Effort towards socially valuable applications is greater under the procurement system than the grant system, because if the firm has only project B, it cannot take part in the contest under a procurement system whilst it can under a grant system. In other words, the lack of a fall-back option strengthens the firm's incentives towards socially valuable applications under the procurement system. Effort towards profitable applications is instead greater under the grant system than the procurement system, because the firm's gain from finding a suitable application is higher when the project is also eligible for public funds, as under the grant system.

6.2 Project size

We have so far assumed that the firms are capable of implementing highly profitable projects with their own funds (Assumption A1). However, large size projects may require significant capital investments, as in the US example of supercomputers. To consider the possibility that firms are unable to cover the cost of implementation with private funds, we now replace (A1) with the following assumption:

$$k > \mu^H > \mu^L. \tag{A2}$$

Assumption (A2) implies that no project will be implemented in the absence of public financing and thus the outside option of all players is zero.

In this context, only the winning firm implements the project and therefore there is no crowding-out effect. The steering effect is unequivocally good for welfare as it does not involve any downside: it makes no difference if project A is implemented with public funds by a firm in state (A) in lieu of a firm in state (AB), as in either case only an A project is implemented. Furthermore, it is now socially desirable to use public funds to implement project B when a project of type A is not available.

Therefore, with large projects a different trade-off may arise. On the one hand, a procurement system induces firms in (AB) to always submit A instead of B, which is the most socially valuable project, whilst a grant system does not. On the other hand, a grant system may generate less valuable projects if firms in state (AB) submit B rather than A, but it allows to implement projects B when no project A is available.

The two policies are formally compared in the following proposition.

Proposition 3 *With large projects, a procurement system is never optimal for $v > \breve{v}$, where:*

$$\breve{v} \equiv \hat{v} - \frac{1}{k\mu^H}\left(\mu^H - k\right)\Delta_\mu < \hat{v}.$$

For $v \leq \breve{v}$, a procurement is the preferred policy if the projects address large social needs but have little profitability ($\Delta_u - \Delta_\mu$ is high), the cost of public funds is high (λ is large), and socially valuable projects are likely to be available ($P_{AB} + P_A$ is high).

Proof: see the Appendix.

When $v > \breve{v}$, which is smaller than $\hat{v}$ as there is no opportunity cost of implementing A, the grant system becomes strictly preferred to the procurement system as firms in (AB) submit A, exactly as with procurement. If instead $v \leq \breve{v}$, then the equilibrium under the grant system is $Eq^{Gr}(\sigma_B)$ whilst it is $Eq^{\Pr}(\sigma_A)$ under the procurement system. The trade-off between implementing A instead of B - thus gaining $\Delta_u - \Delta_\mu$ - when the state is (AB) and implementing B instead of nothing - thus gaining $w^{LH} - (1+\lambda)\,k$ -when the state is (B) therefore arises. This explains the condition in the proposition.

Overall, as crowding out is no longer a concern and instead it is valuable to finance also projects of type B, the procurement system is less likely to be optimal with large projects than in our baseline case.

Note that our setup also allows us to consider the opposite case of particularly small projects. Suppose that (A1) holds but assume:

$$\mu^H - k > \mu^L - k > 0,$$

In words, both projects are now privately profitable. The market allocation would still be inefficient as all firms in (AB) would implement a type B project, whilst a type A project would be preferable. However, the scope for public intervention would be rather limited: now full crowding would occur not just by financing a firm in (B) but also by financing a firm in (A), as this latter firm would pursue its available project A also absent the subsidy.

6.3 Aligned preferences

Suppose that preferences are aligned: project A now yields μ^H whilst project B yields μ^L. Both the public authority and the firms prefer a type A project. Further assume that $u_L > 0$ and $w_L \equiv u_L + \mu_L > k$ so that it implementing project A is socially valuable. The expected social welfare under the market option is now:

$$\hat{W}^0 = \begin{cases} (1-P_B^n)u^H + n(1-P_B)\left(\mu^H - k\right) & \text{Under } (A1) \\ 0 & \text{Under } (A2) \end{cases}$$

where $n(1-P_B)$ is the number of A projects implemented by the industry, as a project of type A will be implemented whenever at least one firm is either in state (A) or in state (AB) under (A1) whilst no project is implemented under (A2). The following proposition then holds under both (A1) and (A2).

Proposition 4 *With aligned preferences, a grant system is optimal both for the public authority and for welfare.*

Delegating the choice of the project to the firm, through a grant system, ensures that the most socially valuable projects are implemented because they are also the most profitable ones, and that less valuable projects are implemented when no better project is available. As a result, the procurement is always outperformed by a grant system. As first argued by Aghion and Tirole (1997), delegation is superior to centralization when preferences are aligned. This result is also consistent with the insight in Armstrong and Vickers (2010) that restricting project choice may be less beneficial when more weight is put on the agent's welfare.[20]

7 Conclusions

Motivated by a renewed policy interest towards alternative forms of government intervention to foster innovation, we have derived the conditions for procurement of innovation to be effective as an innovation policy instrument and preferable to a grant system. We have shown that which system is preferable depends on the interplay between (i) an investment effect (b) a

[20] However, as the crowding-out effect is still present under (A1), it may now happen that it is better for the public authority not to finance any project at all. Note that undertaking a grant system rather than abstaining from providing the firm with public funding yields the social benefits of the additional investment in project B when A is not available, which occurs with probability P_B^n, but it comes at the cost of financing project A with public funds, thereby crowding out private funds, with complementary probability $1-P_B^n$. The expected welfare is therefore:

$$\hat{W}^{Gr}(\sigma_A) = \hat{W}^0 + P_B^n[w_L - (1+\lambda)\,k] - (1-P_B^n)\,\lambda k,$$

and the grant system dominates non-intervention only if:

$$\hat{W}^{Gr} \geq \hat{W}^0 \Leftrightarrow w_L \geq k + \frac{\lambda k}{P_B^n}. \tag{6}$$

This holds when the cost of public fund is not very large, the probability that all firms are only able to implement a project of type B is sufficiently high, and when competition is not too fierce.

crowding-out effect and (c) a steering effect. The first one takes place when public funds are used to support projects that otherwise would not be carried out. The second effect occurs when firms instead of using private funds end up spending scarce public ones. The steering effect happens when the existence of public funds changes the firms' investment towards projects that are aligned with the preferences of the designer.

Our analysis has emphasized how procurement of innovation can be effective at fostering innovation but it is often dominated by a system of grants. In particular, the scope for public procurement is greater for projects that are highly socially valuable but of limited profitability, as then it boosts investment whilst minimizing the risk of crowding out and of "picking the wrong winner".

Our results have clear testable implications. First, crowding out of R&D investment is greater with unconditional R&D subsidies rather than procurement, especially for small size projects. Second, procurement is mainly used for socially useful projects whilst subsidies finance more commercially valuable ones. Third, R&D subsidies are most effective in financing basic research, whilst procurement is most effective in financing applied research with socially valuable applications.

Throughout the paper, we have assumed that the public authority is benevolent, competent and it aims at maximizing consumer surplus. This has led us to show that public procurement should be directed in areas where the private sector's returns are low, whilst social returns are high. However, pressures within public agencies for high 'success rates' in contract awards may lead to the use in R&D funding decisions of selection criteria that put heavy weight on factors that are correlated positively with high expected rates of return to private R&D funding. Furthermore, as emphasized by Bruce et al. (2018), the type of R&D financing may depend on the competence of the public authority. As shown in Decarolis et. al (2019), competency is a crucial ingreadient of success in R&D contracts. In this regard, it would be interesting to extend the analysis to the possibility that the authority's objectives differ from consumer surplus maximization and study the role of competency in project decision making.

Appendix

Proof of Lemma 1

(i) *Equilibrium* $Eq^{Gr}(\sigma_A)$. Using equations (1) and (2), $\pi^{Gr}_{AB}(\sigma_A;\sigma_A) \geq \pi^{Gr}_{AB}(\sigma_B;\sigma_A)$ requires $v \geq \tilde{v}$, where:

$$\tilde{v} \equiv \frac{\gamma_B(\sigma_A)}{\gamma_A(\sigma_A)} = \frac{(1-P_B)P_B^{n-1}}{1-P_B^n}.$$

(ii) *Equilibrium* $Eq^{Gr}(\sigma_B)$. Similarly, $\pi^{Gr}_{AB}(\sigma_B;\sigma_B) \geq \pi^{Gr}_{AB}(\sigma_A;\sigma_B)$ requires $v \leq \hat{v}$, where:

$$\hat{v} \equiv \frac{\gamma_B(\sigma_B)}{\gamma_A(\sigma_B)} = \frac{P_A(1-P_A)^{n-1}}{1-(1-P_A)^n}. \tag{7}$$

Note that $\tilde{v}$ and $\hat{v}$ take the form: $V(x,n) = \frac{x(1-x)^{n-1}}{1-(1-x)^n}$ with $x = P_A + P_{AB}, P_A$, respectively, and with:

$$\frac{\partial V(x,n)}{\partial x} = -\frac{(1-x)^n\left[(1-x)^n + nx - 1\right]}{[1-(1-x)^n]^2(1-x)^2},$$

which is negative if

$$h(x,n) = (1-x)^n + nx - 1 > 0.$$

This always holds as $h(0,n) = 0$ and

$$\frac{\partial h(x,n)}{\partial x} = -n[(1-x)^{n-1} - 1] > 0.$$

Therefore, $\hat{v} = \tilde{v}$ at $P_{AB} = 0$ and $\hat{v} \geq \tilde{v}$ for $P_{AB} \geq 0$. It then follows that for $v \in [\tilde{v}, \hat{v})$, both $Eq^{Gr}(\sigma_A)$ and $Eq^{Gr}(\sigma_B)$ are Bayesian-Nash equilibria. However, $Eq^{Gr}(\sigma_B)$ is payoff-dominant, as (from (1) and (2)):

$$\begin{aligned}\pi^{Gr}_{AB}(\sigma_B;\sigma_B) &\geq \pi^{Gr}_{AB}(\sigma_A;\sigma_A),\\ \frac{\gamma_B(\sigma_B)}{\gamma_A(\sigma_A)} &> \hat{v} \equiv \frac{\gamma_B(\sigma_B)}{\gamma_A(\sigma_B)} \geq v,\end{aligned}$$

which holds since:

$$\gamma_A(\sigma_B) \equiv \frac{1-(1-P_A)^n}{nP_A} > \frac{1-P_B^n}{n(1-P_B)} = \frac{1-(1-(P_A+P_{AB}))^n}{n(P_A+P_{AB})} \equiv \gamma_A(\sigma_A).$$

(iii) It follows from $\hat{v}$ (equation 7) being decreasing with n:

$$\frac{\partial \hat{v}}{\partial n} = \frac{P(1-P_A)^{n-1}\log[1-P_A]}{1-(1-P_A)^n} \leq 0. \blacksquare \tag{8}$$

Proof of Proposition 1

Let $\delta^{In} \equiv w_{HL} - (1+\lambda)k$ denote the investment effect, $\delta^{Cr} \equiv \lambda k$ the crowding out effect and $\delta^{St} \equiv (\mu^H - k)$ the steering effect. Let $p_a \equiv P_B^n$ and $p_b \equiv (1 - P_A)^n$. Under the equilibria $Eq^{Gr}(\sigma_B)$, $Eq^{Gr}(\sigma_A)$ and $Eq^{Pr}(\sigma_i)$, the expected welfare is respectively:

$$W^{Gr}(\sigma_B) = W^0 + (1 - p_b)\,\delta^{In} - p_b\delta^{Cr}. \tag{9}$$

$$W^{Gr}(\sigma_A) = W^0 + (1 - p_a)\,\delta^{In} - p_a\delta^{Cr} - \frac{P_{AB}}{1 - P_B}(1 - p_a)\,\delta^{St}. \tag{10}$$

$$W^{Pr}(\sigma_i) = W^{Gr}(\sigma_i) + p_i\delta^{Cr}, \text{ for i=A,B.} \tag{11}$$

As $W^{Pr}(\sigma_i) > W^{Gr}(\sigma_i)$, the procurement system is preferable for $v \notin (0, \hat{v})$. For $v \in (0, \hat{v})$, $W^{Pr}(\sigma_A) > W^{Gr}(\sigma_B)$ if and only if:

$$\begin{aligned}
W^{Gr}(\sigma_A) + p_a\delta^{Cr} &> W^{Gr}(\sigma_B) \\
(p_b - p_a)\left(\delta^{In} + \delta^{Cr}\right) + p_a\delta^{Cr} &> \frac{P_{AB}}{1 - P_B}(1 - p_a)\,\delta^{St} \\
\delta^{In} + \frac{p_b}{p_b - p_a}\delta^{Cr} &> \frac{P_{AB}}{1 - P_B}\frac{1 - p_a}{p_b - p_a}\delta^{St}
\end{aligned}$$

which can also be written as:

$$u^H - \Delta_\mu > (\eta - 1)\,\delta^{St} - \frac{p_a}{p_b - p_a}\delta^{Cr}, \tag{12}$$

where:

$$\begin{aligned}
\eta &\equiv \frac{1 - P_B - P_A}{1 - P_B}\frac{1 - P_B^n}{(1 - P_A)^n - P_B^n} \\
&= \frac{1 - P_B - P_A}{1 - P_B}\frac{(1 - P_B)\left(1 + P_B + ..P_B^{n-1}\right)}{(1 - P_A - P_B)\left[(1 - P_A)^{n-1}P_B + (1 - P_A)^{n-2}P_B^2 + ... + P_B\right]} \\
&= \frac{\left(1 + P_B + ..P_B^{n-1}\right)}{\left[(1 - P_A)^{n-1}P_B + (1 - P_A)^{n-2}P_B^2 + ... + P_B\right.} \geq 1.
\end{aligned}$$

Finally, from (11) and (9), using (10), we obtain:

$$\begin{aligned}
W^{Pr}(\sigma_A) &\geq W^0 \Leftrightarrow \Delta_u - \Delta_\mu - \lambda k \geq -\frac{P_A}{1 - P_B}(\mu^H - k), \\
W^{Pr}(\sigma_B) &\geq W^0 \Leftrightarrow \Delta_u - \Delta_\mu - \lambda k \geq -(\mu^H - k).
\end{aligned}$$

Both conditions are satisfied in the light of (3). ■

Proof of Proposition 2

(i) We show that $e^{Gr}(\sigma_h) > e^{Pr}(\sigma_h)$. Observes that:

$$\Pi^J(\sigma_h) = \sum_i P_i \left[\left(1-\rho_i^J\right) \pi_i^J(\sigma_h) + \rho_i^J \pi_{AB}^J(\sigma_h) - \frac{\left(\rho_i^J\right)^2}{2} \right],$$

$$\begin{aligned}
\Pi^{Gr}(\sigma_h) &= \sum_i P_i \left[\left(1-\rho_i^{Gr}\right) \pi_i^{Gr}(\sigma_h) + \rho_i^{Gr} \pi_{AB}^{Gr}(\sigma_h) - \frac{\left(\rho_i^{Gr}\right)^2}{2} \right], \\
&\geq \sum_i P_i \left[\left(1-\rho_i^{Pr}\right) \pi_i^{Gr}(\sigma_h) + \rho_i^{Pr} \pi_{AB}^{Gr}(\sigma_h) - \frac{\left(\rho_i^{Pr}\right)^2}{2} \right], \\
&> \sum_i P_i \left[\left(1-\rho_i^{Pr}\right) \pi_i^{Pr}(\sigma_h) + \rho_i^{Pr} \pi_{AB}^{Pr}(\sigma_h) - \frac{\left(\rho_i^{Pr}\right)^2}{2} \right] \\
&= \Pi^{Pr}(\sigma_h).
\end{aligned}$$

The first inequality owes to $\rho_i^{Gr}(\sigma_B)$ being the maximizer of $\Pi_i^{Gr}(\sigma_B)$, the second owes to $\pi_i^{Gr} \geq \pi_i^{Pr}$.

(ii) Consider the equilibrium strategy σ_A. Recall that in state (A), we have: $\pi_A^{Pr}(\sigma_A) = \pi_A^{Gr}(\sigma_A) = \gamma_A(\sigma_A)\mu^L$ whilst in state (AB): $\pi_{AB}^{Pr}(\sigma_A) = \pi_{AB}^{Gr}(\sigma_A) = \gamma_A(\sigma_A)\mu^L + (1-\gamma_A(\sigma_A))\left(\mu^H - k\right)$. Therefore, the effort in applied research in state A under the equilibrium strategy σ_A is given by:

$$\begin{aligned}
\rho_A^{Pr}(\sigma_A) &= \rho_A^{Gr}(\sigma_A) \equiv \pi_{AB}^{Pr}(\sigma_A) - \pi_A^{Pr}(\sigma_A), \\
&= (1-\gamma_A(\sigma_A))\left(\mu^H - k\right).
\end{aligned}$$

Now consider the firm in state (B). Recall that $\pi_B^{Pr}(\sigma_A) = \mu^H - k$, whilst $\pi_B^S(\sigma_A) = \mu^H - (1-\gamma_B(\sigma_A))k$ Therefore, the effort in applied research in state B under the equilibrium strategy σ_A is given by:

$$\begin{aligned}
\rho_B^{Pr}(\sigma_A) &\equiv \pi_{AB}^{Pr}(\sigma_A) - \pi_B^{Pr}(\sigma_A), \\
&\quad \gamma_A(\sigma_A)(k - \Delta\mu) \\
\rho_B^{Gr}(\sigma_A) &= \pi_{AB}^{Gr}(\sigma_A) - \pi_B^S(\sigma_A) \\
&= \gamma_A(\sigma_A)(k - \Delta\mu) - \gamma_B(\sigma_A)k < \rho_B^{Pr}(\sigma_A).
\end{aligned}$$

Consider the equilibrium strategy σ_B. Recall that in state (A), we have: $\pi_A^{Pr}(\sigma_B) = \pi_A^{Gr}(\sigma_B) = \gamma_A(\sigma_B)\mu^L$, whilst in state (AB): $\pi_{AB}^{Pr}(\sigma_B) = \mu^H - k$

and $\pi_{AB}^{Gr}(\sigma_B) = \mu^H - (1-\gamma_B(\sigma_B))\,k$. Therefore, the effort in applied research in state (A) under the equilibrium strategy σ_B is given by:

$$\begin{aligned}
\rho_A^{Pr}(\sigma_B) &= \pi_{AB}^{Pr}(\sigma_B) - \pi_A^{Pr}(\sigma_B),\\
&= \mu^H - k - \gamma_A(\sigma_B)\,\mu^L\\
\rho_A^{Gr}(\sigma_B) &\equiv \pi_{AB}^{Gr}(\sigma_B) - \pi_A^{Gr}(\sigma_B),\\
&= \mu^H - (1-\gamma_B(\sigma_B))\,k - \gamma_A(\sigma_B)\,\mu^L,\\
&> \rho_A^{Pr}(\sigma_B).
\end{aligned}$$

Now consider the firm in state (B). Recall that $\pi_B^{Pr}(\sigma_B) = \pi_B^S(\sigma_B) = \gamma_B(\sigma_B)\,\mu^H$, Therefore, the effort in applied research in state B under the equilibrium strategy σ_B is given by:

$$\begin{aligned}
\rho_B^{Pr}(\sigma_B) &= \rho_B^{Gr}(\sigma_B) = \pi_{AB}^{Pr}(\sigma_B) - \pi_B^{Pr}(\sigma_B),\\
&= 0.
\end{aligned}$$

It follows from the above that:

$$\begin{aligned}
\rho_A^{Pr}(\sigma_A) &= \rho_A^{Gr}(\sigma_A) \text{ and } \rho_A^{Gr}(\sigma_B) > \rho_A^{Pr}(\sigma_B)\\
\rho_B^{Pr}(\sigma_B) &= \rho_B^{Gr}(\sigma_B) \text{ and } \rho_B^{Gr}(\sigma_A) < \rho_B^{Pr}(\sigma_A). \quad \blacksquare
\end{aligned}$$

Proof of Proposition 3

First we prove the following Lemma.

Lemma 3 *Let (A2) hold. Under a grant system with conflicting preferences, there exists a unique symmetric Coalition-Proof Bayesian Nash equilibrium characterized as follows: (i) If $v > \breve{v}$:*

$$\breve{v} \equiv \hat{v} - \frac{1}{k\mu^H}\left(\mu^H - k\right)\Delta_\mu,$$

competing firms play $Eq^{Gr}(\sigma_A)$;
(ii) If instead $v \le \breve{v}$, competing firms play $Eq^{Gr}(\sigma_B)$.

Proof:
(i) *Equilibrium $Eq^{Gr}(\sigma_A)$.* Under (A2), $\pi_{AB}^{Gr}(\sigma_A;\sigma_A) = \gamma_A(\sigma_A)\mu^L$ and $\pi_{AB}^{Gr}(\sigma_B;\sigma_A) = \gamma_B(\sigma_A)\mu^H$. Therefore, $Eq^{Gr}(\sigma_A)$ is a Bayesian-Nash equilibrium if:

$$\frac{\gamma_A(\sigma_A)}{\gamma_B(\sigma_A)} \equiv \frac{1-P_B^n}{(1-P_B)P_B^{n-1}} \ge \frac{\mu^H}{\mu^L}.$$

(ii) *Equilibrium* $Eq^{Gr}(\sigma_B)$. Under (A2), $\pi^{Gr}_{AB}(\sigma_B;\sigma_B)=\gamma_B(\sigma_B)\mu^H$ and $\pi^{Gr}_{AB}(\sigma_A;\sigma_B)=\gamma_A(\sigma_B)\,\mu^L$. Therefore, $Eq^{Gr}(\sigma_B)$ is a Bayesian-Nash equilibrium if:

$$\frac{\mu^H}{\mu^L}\geq\frac{1-(1-P_A)^n}{P_A(1-P_A)^{n-1}}\equiv\frac{\gamma_A(\sigma_B)}{\gamma_B(\sigma_B)}.$$

In the interval $[\tilde{v},\hat{v}]$, $Eq^{Gr}(\sigma_B)$ is payoff dominant as:

$$\begin{aligned}\pi^{Gr}_{AB}(\sigma_A,\sigma_A) &\leq \pi^{Gr}_{AB}(\sigma_B,\sigma_B),\\ (1-P^n_B)\mu^L+P^n_B\mu^H &\leq (1-P_A)^n\mu^H+\big(1-(1-P_A)^n\big)\mu^L,\\ \mu^L &\leq \mu^H.\end{aligned}$$

To obtain the expression in Lemma 3, note that:

$$v-\frac{\mu^L}{\mu^H}=\frac{1}{k\mu^H}\left(k-\mu^H\right)\left(\mu^H-\mu^L\right),$$

which implies

$$\begin{aligned}v &\geq \hat{v}-\frac{1}{k\mu^H}\left(\mu^H-k\right)\Delta_\mu=\frac{\gamma_B(\sigma_B)}{\gamma_A(\sigma_B)}+v-\frac{\mu^L}{\mu^H}\\ \Leftrightarrow &\quad \frac{\mu^L}{\mu^H}\geq\frac{\gamma_B(\sigma_B)}{\gamma_A(\sigma_B)}.\blacksquare\end{aligned}$$

Now consider the equilibrium welfare. Under Equilibrium $Eq^{Gr}(\sigma_i)$, project A is financed with probability $(1-p_i)$ and B with complementary probability. Expected welfare is therefore:

$$W^{Gr}(\sigma_i)=(1-p_i)\,w_{HL}+p_iw_{LH}-(1+\lambda)\,k.$$

Under procurement, the firms submit A whenever they have it, and therefore welfare is:[21]

$$\begin{aligned}W^{Pr}(\sigma_A) &= (1-p_a)\left[w_{HL}-(1+\lambda)\,k\right]\\ &= W^{Gr}(\sigma_A)-p_a[w_{LH}-(1+\lambda)k].\end{aligned}$$

It follows that $W^{Gr}(\sigma_A)>W^{Pr}(\sigma_A)$ and $W^{Pr}(\sigma_A)>W^{Gr}(\sigma_B)$ if:

$$\frac{\Delta_u-\Delta_\mu}{w_{HL}-(1+\lambda)k}>\frac{p_a}{p_b},$$

which requires $\Delta_u-\Delta_\mu$, P_{AB} and λ are high. $\blacksquare$

[21] In the below expressions, $w_{HL}=u_H+\mu_L$ and $w_{LH}=u_L+\mu_H$.

Proof of Proposition 4

Under (A1) and the procurement system, the equilibrium is clearly $Eq^{Pr}(\sigma_A)$ and therefore there is full crowding out of private investment, leading to social welfare:

$$\hat{W}^{Pr}(\sigma_A) = (1 - P_B^n)\left(u^H - \lambda k\right) + n(1 - P_B)\left(\mu^H - k\right) < W^0.$$

Under the grant system, the equilibrium is $Eq^{Gr}(\sigma_A)$ as project B yields lower profits and a lower probability of winning. Expected welfare is therefore:

$$\hat{W}^{Gr}(\sigma_A) = \hat{W}^{Pr}(\sigma_A) + P_B^n[w_L - (1 + \lambda)\,k],$$

which is greater than $\hat{W}^{Pr}(\sigma_A)$.

Under (A2), the inequality continues to hold; the only difference is that $\hat{W}^{Pr}(\sigma_A) > \hat{W}^0 = 0$ and therefore under the procurement system brings an increase in welfare compared to nonintervention.■

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