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Rewards versus intellectual property rights when commitment is limited☆

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ABSTRACT

This paper compares the performance of a variety of innovation policy instruments when the government cannot commit to transfer cash rewards to an innovator and has the option to divert resources to alternative investments. In a dynamic environment in which government's investment opportunities evolve stochastically, we provide conditions under which the optimal mechanism is a price regulation system where the inventor owns intellectual property and receives a cash transfer when price equals marginal cost. We illustrate how a dynamic complementarity between cash rewards and intellectual property may arises when the government's budget is limited and monopoly distortions are not too severe. We discuss how other forms of complementarity between cash transfers and intellectual property may emerge, with patent rights serving as a discipline device that ensures the payment of the reward.

1. Introduction

A central class of problems in the economics of innovation literature examines the role of government policies to incentivize R&D investments and the development of new products. Traditionally, the literature has studied this issue comparing a variety of policy tools in situations where the innovator has an information advantage over the government in understanding the quality of new products (Scotchmer, 1999; Shavell and Ypersele, 2001). This paper departs from this standard modelling approach and focuses instead on situations where the government faces a commitment problem. Specifically, we examine the performance of innovation policies in a model where the planner cannot commit to transferring resources to the innovator and faces the option to divert its budget to alternative welfare-generating projects.

The use of innovation prizes has increased substantially during the past decade with a large number of philanthropists entering the business of rewarding innovators (McKinsey, 2009). The Gates Foundation, Qualcomm and Nokia have offered multi-million dollar prizes for children immunization and the development of affordable medical devices. In the public sector, one of the most important examples of innovation prizes is the 2004 Darpa Grand-Challenge in which a $1 million prize was offered to the team that built a self-driving car that drove 150 miles through the Mojave Desert the fastest. The goal of this innovation prize was to obtain technologies useful for the US defense sector that was looking to make

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ground military forces autonomous. This Darpa challenge is often described as the prize that jump-started the self-driving car industry (Davies, 2017). Former US President Obama's Strategy for American Innovation strongly encouraged the use of innovation prizes, and the America Competes Reauthorization Act of 2011 provided all federal agencies with power to offer innovation prizes (Williams, 2012). Since then, the U.S. government has implemented more than 1000 challenges in more than 100 federal agencies.[1]

Innovation prizes are a natural setting in which a regulator may not have the ability to make credible, or enforceable, promises about the payment of a prize. The 1714 longitude prize, in which the winning inventor had to request the king's intervention and waited 47 years to receive the compensation, is probably the most well-known example of this issue. More recently, the idea that commitment is crucial for the success of innovation prizes has been emphasized in relation to vaccine development and human genome sequencing (Kremer and Glennerster, 2004; Kaiser, 2013). To motivate the theoretical analysis, Section 3 discusses a number of reasons why commitment concerns are likely to be more severe when the government rewards innovators with cash prizes rather than property rights. For example, the political economy returns that the government can obtain by diverting cash prizes toward lower taxes and other policies offering immediate political gains are likely to exceed those obtained reneging intellectual property protection (Roin, 2014).

We develop a dynamic model in which a social planner and one innovator have complete information about the value of a technology and examine how different policies affect the likelihood of developing the technology as well as the price at which the technology will be sold. A key property of our model is that an alternative opportunity for government resources may emerge stochastically over time. Initially there is no alternative use for government funds but, as time passes, the planner may divert funds from the innovator to other constituencies. These shocks generate a commitment problem, similar to the dynamic inconsistency of policy makers which is central to a growing literature in political economy (Avador et al., 2006; Halac and Yared, 2014; Bisin et al., 2015).

Following Shavell and Ypersele (2001), we compare three main policy regimes: (i) the patent system which gives the innovator the exclusive right to sell the product resulting from the innovation, (ii) the simple reward system in which the planner pays the innovator and the innovation is placed in the public domain and (iii) the optional reward system under which the innovator can choose between a patent and a reward. As emphasized by the innovation literature, a patent system creates two types of distortions. First, monopoly rights generate a deadweight loss in the product market. Second, the innovator will underinvest in research because monopoly profits are less than that the social surplus. The reward system has the potential to remove both of these distortions because the planner can transfer to the innovator rents which are larger than monopoly profits, and absence of monopoly rights eliminates the deadweight loss. But payment of the reward is not credible in our model, because the planner has strong incentives to divert resources to an alternative investment once the innovation has been placed in the public domain.

We also explore the properties of an alternative policy regime which we label price regulation system. In this regime, the innovator keeps the patent rights for multiple periods, and the planner pays a per-period reward only if the innovator charges the competitive price. As discussed in Roin (2014), most developed countries use similar approaches to provide access to prescription drugs to their citizens. We show that, in a number of circumstances, the price regulation system may perform better than patents and simple rewards because it guarantees monopoly profits to the innovator even when a shock induces the planner to divert all its resources to alternative uses. We show that when the planner's budget is large enough relative to the monopoly profits and the alternative investment, the price regulation system is an optimal mechanism implementing the first best welfare level. At the same time, our analysis also identifies situations in which simpler rewards that do not combine patents and cash transfers are preferable to price regulation. This occurs in cases in which the planner's budget is not large enough to keep the patent dormant if a shock occurs, and the deadweight loss in the product market is large.

Our analysis of the price regulation system provides insights on how the reward schedule should be shaped over time to maximize welfare. Government may prefer front-loading the rewards when facing a substantial budget constraint and when monopoly distortions are not severe. In this case a dynamic complementarity between patents and prizes arises, and innovation incentives are maximized when the government transfers all the available cash to the innovators and also let them enjoy monopoly profits. Conversely our model suggests that spreading more evenly a reward over time may be preferable when monopoly pricing generates large dead-weight losses.

We discuss an extension of the model in which the outside alternative provides only limited welfare. We show that in this case optional rewards are more effective at spurring innovation and can generate more research incentives and welfare than patents and simple rewards. This finding highlights an additional complementarity between cash transfers and patents, with patents serving the role of a commitment device which disciplines the planner and guarantees the payment of the reward.

The paper is organized as follows. Section 2 reviews the related literature. Section 3 discusses the key assumption of our theoretical framework. Section 4 presents the dynamic model with stochastic shocks. Section 5 describes the innovation policy instruments used by the planner. Section 6 compares the various policy regimes. Section 7 discusses an extension of

[1] The source for this statistics is www.challenge.gov which also provides a comprehensive list of prize competitions currently open. A prominent example of a recent inducement prize is the KidneyX competition, the result of a partnership between the US Department of Health and Human Services and the American Society of Nephrology which asked innovators to create technologies that can replicate normal kidney functions and improve patient quality of life.

our model that considers alternative investments generating low welfare. Section 8 concludes discussing the implications of our findings for innovation policy and the design of innovation prizes.

2. Related literature

Our paper is related to a number of theoretical studies in the law and economics literature that examine how policy mechanisms affect innovation incentives.

Wright (1983) compares prizes, patents and research contracts as mechanisms to encourage innovation. The main result of his analysis is that any of these three policy tools can be optimal depending on the trade-off between research duplication, monopoly deadweight loss and asymmetric information between the planner and the innovator. Shavell and Ypersele (2001) provide a comparison of prizes and patents as mechanisms to incentivize innovation. They show that neither system is superior and that a mechanism under which innovators can choose between prizes and patents generates often more welfare than a patent system.

Scotchmer (1999) and Cornelli and Schankerman (1999) exploit a mechanism design approach to examine the optimal policy in the presence of information frictions between the planner and the innovator. They show that policies in which the innovator chooses from a menu of protections are typically superior. Building on these studies, Hopenhayn and Mitchell (2001) study how to screen technologies through menus of breadth and length. Hopenhayn et al. (2006) examine the optimal patent design in a model where innovation is cumulative, involving contributions of multiple innovators. In their model the optimal reward might include payments between innovators but typically not from the planner to the innovators, like a prize. Llanes and Trento (2011, 2012) extend this analysis assuming that each technology builds on several previous innovations. Weyl and Tirole (2012) study the optimal reward structure in the presence of multidimensional heterogeneity and non-manipulable market outcomes. They show that the optimal policy requires some market power but not full monopoly profits.[2]

A number of studies have examined the trade-off between patents and prizes, but attempted to see whether external signals might allow prizes to dominate patents. Kremer (1998) examines a patent auction mechanism to elicit information on the value of the innovation. Chari et al. (2012) compare prizes and patents when the planner can observe market signals over time. Their main finding is that patents are necessary when the market demand can be manipulated by the innovator. Galasso et al. (2016) show how a patent buyout that exploits information from market outcomes as a guide to the payment amount can be effective at determining both marginal and total willingness to pay of consumers and can generate the right innovation incentives.

Galasso et al. (2018) develop a model in which innovative effort is multi-dimensional and only a subset of innovation tasks can be measured and contracted upon. They show that in this environment patent rights and cash rewards are complements, and that combining the two instruments may generate larger welfare than patent races or prizes requiring technologies to be placed in the public domain. This study also uncovers a tendency for patent races to encourage speed of discovery over quality of innovation, which can be corrected by a joint use of patents and cash rewards.

In the law literature, the idea that intellectual property may serve as a commitment device has been originally discussed in Roin (2014) in a comprehensive analysis of the legal debate comparing intellectual property and prizes.

3. Commitment issues with innovation prizes

The key assumption in our analysis will be that the planner lacks full commitment power on the payment of cash prizes, but can credibly commit to reward innovators with patent rights.

Innovation prizes are a natural setting in which a regulator may not have the ability to make credible, or enforceable, promises about the payment of a prize. The story of the longitude prize is perhaps the most legendary example of the commitment problems associated with cash prizes. In 1714 the British government offered a large reward for an accurate means of gauging longitude at sea. The government established an ad-hoc committee – the Board of Longitude – to evaluate the proposed technologies and administer the prize. The best solution came from John Harrison – a self-taught craftsman from a small Lincolnshire village and with no formal academic education - who challenged leading astronomy scholars with a novel approach to address the longitude problem (Cattani et al., 2017). As an outsider to the astronomy academic community, Harrison encountered numerous obstacles in his dealings with the Board of Longitude, and a full 47 years elapsed before Harrison actually received compensation. The king's intervention and an Act of Parliament were required to settle the dispute with the Board and for Harrison to obtain the reward (Khan, 2015; Cattani et al., 2017).

More recently, the idea that commitment is crucial for the success of innovation prizes has been emphasized by prize advocates in a number of contexts. For example, Kremer and Glennerster (2004) highlight how prizes for the development of vaccines will increase research activity only if developers believe that the sponsor will not renege once desired products have been developed and research costs sunk. Issues of commitment and credibility of prizes have also been discussed in the press in 2013, when the X-Prize foundation cancelled a prize, announced in 2006, centered on the design of devices that could sequence 100 human genomes in 30 days or less (Kaiser, 2013).

[2] Casadesus-Masanell and Llanes (2011) and Tesoriere and Balletta (2017) examine economic environments in which intellectual property and open innovation co-exist.

There are a number of reasons why commitment concerns are likely to be more severe when the government rewards innovators with cash prizes instead of property rights. First, innovators compete with many more interest groups over public funds than over ownership of a specific technology (Roin, 2014). Second, the political economy returns that the government can obtain by diverting cash resources toward lower taxes and other policies offering immediate political gains are likely to exceed those obtained reneging intellectual property protection.

Even when independent government agencies administer innovation prizes, biases toward particular interest groups may lead to inadequate payout or expropriation, as in the case of the longitudinal prize. Moreover, the legislator may under-reward innovators by inadequately funding the prize agencies (Roin, 2014). Commitment issues are also likely to be present when cash prizes are offered by the private sector. Private prize organizers may favour solutions which score high in few easy-to-measure performance metrics or which have the potential to generate greatest public attention and media exposure, rather than those with higher social welfare (Murray et al., 2012; Galasso et al., 2018).

4. The model

Our setup is a dynamic version of the model developed by Shavell and Ypersele (2001), with the exception that we allow the government to divert money from the innovation investment to an alternative project.

There are $T+1$ periods denoted by $t = 0, 1, \dots, T$. All players discount the future with a common discount factor δ. At $t = 0$ a risk-neutral innovator invests to develop a new product. Let k be the research investment and $p(k)$ with $k \in R_+$, $p'(k) > 0$ and $p''(k) < 0$ be the probability that the innovation investment is successful. A function satisfying these assumptions is $p(k) = k/(k+1)$. If innovation succeeds, a new product can be produced at a constant marginal cost which we normalize to zero.

We indicate with $d(q_t)$ the inverse demand function for the product which lasts from period 1 to period T where q_t is the quantity produced at time t. We assume $d'(q) < 0$ and that monopoly profits and social surplus are positive. A functional form satisfying these assumption is $d(q_t) = 1 - q_t$.

Departing from typical models in the literature, we assume the demand to be known by the innovator and by the planner. Wright (1983) and Shavell and Ypersele (2001) show that asymmetric information between the planner and the innovator may render rewards less effective than intellectual property. Our assumption of complete information allows to isolate the role of commitment when comparing different policy instruments.

If a new product is developed, the first best quantity, q^*, is such that the price equals the marginal cost, i.e., $d(q^*) = 0$. The per-period social welfare generated in the product market at this level of production will be

$$s^* = \int_0^{q^*} d(q)dq.$$

The innovator per-period profits are $\pi(q_t) = q_t d(q_t)$. We indicate with q^P the quantity maximizing the per-period profit and with π^P the maximized profits. The per-period product market welfare generated by this production level is denoted by $s^* - l$ where l captures the deadweight loss generated by monopoly production

$$l = \int_{q^P}^{q^*} d(q)dq.$$

4.1. Public budget and shocks

We assume that the government (social planner) has an exogenous per-period budget, τ, which is large enough to compensate the innovator for the maximum product market surplus created in one period, i.e., $\tau \geq s^*$. Building on Halac and Yared (2014) we assume that in each period $t > 0$ the planner can spend g_t and enter debt b_t subject to the budget constraint

$$g_t = \tau + \delta b_{t+1} - b_t$$

with $b_1 = 0$ and $b_{T+1} = 0$ so that all debts are eventually repaid.

We assume that there is an alternative opportunity which at time $t > 0$ generates surplus $\lambda_t \in \{0, \lambda\}$ with $p(\lambda_1 = 0) = 1 - \alpha$, $p(\lambda_1 = \lambda) = \alpha$ and λ_t determined by the following transition probability for each $t > 1$:

$$p(\lambda_t = \lambda) = \begin{cases} \alpha & \text{if } \lambda_{\tilde{t}} = 0 \quad \text{for each } \tilde{t} < t \\ 0 & \text{else} \end{cases}.$$

This process captures the idea that the alternative investment opportunity may arise only once and that the shock is expected with probability α as long as it has not manifested before.[3] Stochastic shifts in λ can be interpreted as changes in the

[3] For completeness, we also have $p(\lambda_t = 0) = \begin{cases} 1-\alpha & \text{if } \lambda_{\tilde{t}} = 0 \quad \text{for each } \tilde{t} < t \\ 1 & \text{else} \end{cases}.$

opportunity cost of funds for the planner. At time zero the planner has no alternative use for the funds but, as time passes, the opportunity to divert funds from the innovator to other constituencies may arise. These shocks generate a commitment problem, similar to the dynamic inconsistency of policy makers which is central to a growing literature in political economy (Avador et al., 2006; Halac and Yared, 2014; 2018; Bisin et al., 2015). The value of α is a proxy for the commitment problem of the planner. When the planner is a national government, a switch from $\lambda_{t-1} = 0$ to $\lambda_t = \lambda$ may be driven by geopolitical tensions or terrorist attacks requiring higher defence spending, or natural disasters requiring relief spending. When the planner is a non-governmental organization, alternative opportunities may arise in the case of new disease outbreaks requiring a cure.

We assume that the alternative investment requires a fixed investment of ϖ in public funds. The benefits, λ, are net of the investment cost and assumed to be large enough that the planner will always want to invest immediately if the opportunity arises. This is equivalent to assuming that λ is very large relative to l. In Section 7 we show how our results are robust to relaxing this assumption.

We define the total budget available to the planner as

$$B \equiv \frac{1-\delta^T}{1-\delta}\tau$$

and assume that $B \geq \varpi$ so that the budget is large enough to pay for the alternative project.

5. Innovation policies

The objective of the government is to maximize welfare. We examine alternative policy tools which the government can exploit to reward the innovator. In particular, building on a long-standing tradition in the economics of innovation literature our analysis begins by considering: (i) a patent giving the innovator the exclusive right to sell the product resulting from the innovation and (ii) a cash reward paid to the innovator with the innovation placed the public domain (Wright, 1983; Shavell and Ypersele, 2001; Chari et al., 2012; Weyl and Tirole, 2012).

Notice how in our setting, the first best is achieved if the quantity produced is q^* and the research investment, $k(S^*)$, maximizes

$$p(k)S^* - k$$

where $S^* = \sum_{t=1}^{T} \delta^{t-1} s^*$. Moreover, the alternative investment is pursued immediately any time it arises.

In principle, the first best welfare can be implemented if the planner can exploit a broad set of policy tools such as taxing the innovator. For example, the planner can charge a large tax to the innovator if either k differs from $k(S^*)$ or q_t differs from q^*. Below, we show that the first best is typically not obtained if we restrict the planner to use more realistic innovation policy tools.

5.1. Patents

Under a patent regime the innovator has the exclusive right to sell the product resulting from an innovation. The innovator will behave as a monopolist and choose the quantity to maximize profits

$$\sum_{t=1}^{T} \delta^{t-1} q_t d(q_t)$$

which implies that q^P is produced in each period. The optimal innovation investment in the presence of patents, $k(\Pi^P)$, solves

$$\max_k p(k)\Pi^P - k$$

where $\Pi^P = \sum_{t=1}^{T} \delta^{t-1} \pi^P$.

The welfare generated by the patent system is

$$\begin{aligned} W^P &= p(k(\Pi^P)) \left[\sum_{t=1}^{T} \delta^{t-1}(s^* - l) \right] - k(\Pi^P) + \alpha\lambda \sum_{t=1}^{T} ((1-\alpha)\delta)^{t-1} \\ &= p(k(\Pi^P))(S^* - L) - k(\Pi^P) + \frac{1-\widetilde{\delta}^T}{1-\widetilde{\delta}}\alpha\lambda \end{aligned}$$

where $L = \sum_{t=1}^{T} \delta^{t-1} l$, and $\widetilde{\delta} = (1-\alpha)\delta$. The stochastic shock has no impact on innovation investments and the welfare generated by the new technologies. This is intuitive, given that the patent system does not affect the budget of the planner.

5.2. Simple rewards

Simple rewards consist in a reward schedule $r_{SR} = (r_1, \dots, r_T)$ in which a cash transfer r_t is paid in period t. The innovator has no property rights on the innovation which is placed in the public domain and made available to a competitive industry. Price will be driven to marginal cost, the total per-period quantity produced will be q^*, and the corresponding per-period product market surplus will be s^*. The reward schedule is announced by the planner before the innovator invests in research to develop the product.

We restrict the planner to offer only one reward schedule and not multiple schedules contingent on whether and when the shock takes place. This is a natural assumption in our setting, because we expect shocks to the opportunity costs of public funds (such as wars or terrorist attacks) to be difficult to describe and contract upon.

We focus our analysis on reward schedules satisfying the following two conditions:

$$\sum_{t=1}^{T} \delta^{t-1} r_t \le B \tag{1}$$

$$B - \sum_{t=1}^{i} \delta^{t-1} r_t \ge \delta^{i-1} \varpi \quad \text{for each } i = 1, \dots, T-1. \tag{2}$$

Condition (1) implies that, in the case in which the shock does not take place, the budget is large enough to pay for the promised reward. Our model also assumes that the planner cannot recover a cash transfer once it has been paid to the innovator. The large social value of the alternative opportunity implies that the planner will save in each period enough resources to implement the alternative investment in case a shock takes place. Condition (2) describes this left-over condition, which assures that in each period i the planner has enough resources to pay for the alternative investment in case the shock takes place in future periods.

If the shock takes place in period i, we assume that the planner transfers to the innovator the minimum between the remaining of the promised rewards r_i for $t \ge i$ and the budget which is not used for the outside investment. Let us denote as $R = \sum_{t=1}^{T} \delta^{t-1} r_t$ the net present value of the rewards if they are all paid by the planner.

The expected reward for the innovator is

$$E(r_{SR}) = (1-\alpha)^T R + \alpha \sum_{t=1}^{T} (1-\alpha)^{t-1} \min\left\{B - \delta^{t-1}\varpi, R\right\}.$$

We say that the reward schedule r_{SR} is *credible* if $B - \varpi \ge R$. In this case $E(r_{SR}) = R$. We say that r_{SR} is *risky* if $B - \varpi < R$. In this case there is at least one period in which the payment is less than the promised reward if the shock occurs.

Proposition 1. *Simple rewards can implement the first best if and only if*

$$B - \frac{1-\tilde{\delta}^T}{1-\tilde{\delta}} \alpha \varpi \ge S^*. \tag{3}$$

Proof. See Appendix. □

The above proposition illustrates how simple rewards can be used to implement the first best, provided that the budget is large enough. If the condition in the proposition is satisfied, a scheduled can be designed that induces the socially optimal research investment with no dead-weight loss in the product market. It is important to notice that the reward schedule does not need to be credible to implement the first best, it only needs to transfer the full product market surplus to the innovator in expectation, i.e., taking into account that not all the promised rewards will be paid if the shock takes place. Indeed, it is possible to characterize a family of risky schedules implementing the first best. Schedules within this family satisfy

$$R = \frac{S^* - \alpha \sum_{t=1}^{i} (1-\alpha)^{t-1} (B - \delta^{t-1}\varpi)}{(1-\alpha)^i}$$

for some $i \in \{1, \dots, T\}$. Intuitively, schedules in this class are paid in full only if the shock takes place after period i (or never takes place). The proof of proposition 1 exploits the case in which $i = T$ (schedules paid in full only if the shock never takes place) to obtain condition (3). Notice how the total payment promised, R, may exceed S^* substantially when the shock is likely to occur (large α) and B is small relative to ϖ.

Simple rewards cannot implement the first best when (3) is not satisfied. We will refer to this case as the *limited budget case*. The maximum expected transfer for the innovator in this case is

$$E(r_{SR}) = B - \frac{1-\tilde{\delta}^T}{1-\tilde{\delta}} \alpha \varpi$$

and the corresponding welfare is

$$W^{SR} = p(k(E(r_{SR})))S^* - k(E(r_{SR})) + \frac{1-\widetilde{\delta}^T}{1-\widetilde{\delta}}\alpha\lambda.$$

The ex-post welfare created in the product market is independent of whether the shock occurs or not. This is because there is no intellectual property and no dead-weight loss. The loss in welfare is entirely determined by the limited budget available to the planner in the case of a shock, which reduces ex-ante research investments and the likelihood that the surplus is created. The extent of the under-investment increases in T and ϖ.

5.3. Optional rewards

Having described two classic innovation policy tools, we introduce now a third policy option: the optional reward. In this regime, the planner offers a reward schedule, r_{OR}, to the innovator before the innovation investment takes place. In period 1 the innovator chooses whether to accept the reward and forego patent protection or to keep the patent. This can be interpreted as giving the option to the innovator to sell the patent to the planner immediately after the patent is granted by the patent office (similar in spirit to the buy-out mechanism proposed in Kremer (1998)). The reward will be chosen by the innovator if $E(r_{OR}) \geq \Pi^P$.

If a simple reward can attain the first best, an optional reward with the same schedule will also generate the first best. This follows immediately from the fact that achieving the first-best requires a schedule generating an expected payoff of S^* which is larger than Π^P.

When the budget is limited, an optional reward regime either generates the welfare of the patent regime or the one of the simple reward regime. Nonetheless, the welfare generated is not necessarily the highest of the two regimes, as the next proposition shows.

Proposition 2. *The optional reward regime may generate W^P even if $W^P < W^{SR}$.*

Proof. Consider a reward schedule r such that $E(r) = \Pi^P - \varepsilon$ with $\varepsilon > 0$. In this case if r is offered as an optional reward ($r_{OR} = r$), the patentee will choose to keep the patent and welfare will be W^P. As $\varepsilon \to 0$ the R&D investment generated by a simple reward with schedule $r_{SR} = r$ approaches the one of the patent but $W^P < W^{SR}$ because of the patent dead-weight loss l. □

The proposition shows that in an optional reward regime the patentee will choose between the patent and the cash prizes only focusing on their expected private returns, which may differ from the welfare levels attained by the two options. This may be particularly likely when the budget of the planner is limited, and the expected return of the reward offered does not exceed the profits from the patent. In this case the innovator will keep the patent even if the welfare loss generated by monopoly distortions is large.

As the budget becomes more limited (i.e., $B \to \varpi$) and the shock becomes more likely ($\alpha \to 1$), the optional reward generates an outcome equivalent to the one of the patent regime.

5.4. Price regulation

A key feature of the three regimes analyzed so far is that either intellectual property generates monopoly distortions (and rents) for T periods, or it is not active for all T periods. In this subsection we will introduce an alternative regime in which intellectual property can potentially be active for a subset of the T periods: the price regulation regime. We define a price regulation system as a reward schedule $r_{PR} = (r_1, \ldots, r_T)$ in which r_t is paid only if $q_i = q^*$ for $i = 1, \ldots, t$. Specifically, the inventor has a patent on the product and a reward is received in period t if the product is sold at competitive price at period t and in all previous periods. Notice how price regulation and optional reward are equivalent when $T = 1$, but differ when $T > 1$. The reward schedule is announced before the innovator invests to develop the new product.

In this policy mechanism, the innovator voluntarily lowers prices toward marginal costs in order to collect cash rewards from the planner. As discussed in Roin (2014), most developed countries use similar approaches to provide access to prescription drugs to their citizens. While pharmaceutical companies retain patent rights, consumer prices are often set by governments which reward patent holders with (sales based) reimbursement from public funds.

In this regime, an important case is the one in which a shock takes place in period i and the planner does not have enough resources to pay all future promised rewards. Specifically, this is the case in which

$$B - \delta^{i-1}\varpi - \sum_{t=1}^{i-1}\delta^{t-1}r_t < \sum_{t=i}^{T}\delta^{t-1}r_t.$$

We assume that in this case rewards will be paid in full up to period $\widetilde{t} - 1$ where $\widetilde{t}$ is defined as the largest x such that

$$\sum_{t=i}^{x-1}\delta^{t-1}r_t < B - \delta^{i-1}\varpi - \sum_{t=1}^{i-1}\delta^{t-1}r_t.$$

The reward for period $\widetilde{t}$, $r_{\widetilde{t}}$, is revised to

$$\widehat{r}_{\widetilde{t}} = \frac{1}{\delta^{\widetilde{t}}}\left(B - \delta^{i-1}\varpi - \sum_{t=1}^{\widetilde{t}-1}\delta^{t-1}r_t\right),$$

and the rewards for periods $\widetilde{t}+1,\ldots,T$ are revised to zero. This assumptions implies that in the case of a shock the planner will reduce future transfers subtracting the resources needed for the alternative investment starting from the last period and going backward.

Proposition 3. *Price regulation can generate the first best if (3) and the following condition jointly hold:*

$$B - \Pi^P \geq \varpi. \tag{4}$$

Proof. Proposition 1 shows that when (3) is satisfied, it is possible to design a schedule that transfer S^* to the innovator in expectation. To implement the first best in a price regulation regime, the expected reward from keeping the patent dormant if a shock occurs in period i, $R - \delta^{T-i}\varpi$, needs to exceed $\sum_{t=1}^{i-1}\delta^{t-1}r_t + \sum_{t=i}^{T}\delta^{t-1}\pi^P$ which is the payoff from switching to monopoly profits using the patent. This rewrites as

$$\sum_{t=i}^{T}\delta^{t-1}(r_t - \pi^P) \geq \delta^{i-1}\varpi.$$

The right hand side is largest when the shock takes place in period 1. In this case the condition rewrites as

$$R - \Pi^P \geq \varpi.$$

Condition (4) follows from the fact that the maximum that can be transferred is B. □

Proposition 3 shows that with price regulation attainment of the first best requires an additional condition to the budget, in addition to the one required for simple rewards. In the simple reward regime, first best can be achieved if the planner has enough resources to transfer the first best product market surplus to the innovator, in expectation. With price regulation, this 'ex-ante' condition needs to be complemented with an 'ex-post' condition on the budget. Specifically, when a shock takes place, the planner needs to have enough resources to compensate the innovator for keeping the patent dormant.

Notice that condition (4) does not depend on α and it is satisfied when the cost of the shock, ϖ, is not too large. Conversely, condition (3) can be satisfied when α is close to zero even when ϖ is large, i.e., when shocks are very costly but unlikely. This difference captures the key feature of the extra constraint associated with price regulation.

Together, conditions (3) and (4) identify lower bounds on the size of the budget required to implement the first best. If these conditions are satisfied, a reward schedule that keeps the patent dormant and that generates the efficient R&D investment can be designed. It is important to notice that, to keep the patent dormant in all T periods, the schedule has to pay a substantial amount of cash in period T. This is because in the case of a shock the planner will trim future transfers starting from the last period, so r_T has to be large enough for the patent not to be used in the last period. Building on this discussion, the following corollary provides a lower bound on r_T.

Corollary 4. *Implementation of the first best requires*

$$r_T \geq \pi^P + \frac{\varpi}{\delta^{T-1}}. \tag{5}$$

Proof. If the shock takes place in period i, the planner the planner will trim future rewards (starting from the one of time T) subtracting the resources needed to pay the alternative investment. Thus, if a shock takes place in period i, the patent will remain dormant in period T only if $\delta^{T-i}r_T - \varpi \geq \delta^{T-i}\pi^P$. This condition is most stringent at $i = 1$ so a requirement to have the patent dormant at T is

$$\delta^{T-1}r_T - \varpi \geq \delta^{T-1}\pi^P$$

that rewrites as (5). □

An implication of corollary 4 is that implementation of the first best through price regulation becomes more challenging as δ gets closer to zero. Intuitively, the resources that need to be subtracted from future payments get larger as δ gets smaller. This implies that keeping the patent dormant up to the last period is more challenging, especially when the shock takes place in the first few periods.

6. Comparing the different policy regimes

This section compares the alternative policy regimes described above. We begin with a simple remark which follows from the fact that a price regulation regime can always replicate a patent regime by setting a reward schedule equal to zero.

Remark 5. The price regulation regime dominates the patent regime.

The above remark, combined with the fact that an optional reward regime either generates the welfare of the patent regime or the welfare of the simple reward regime, implies that the crucial policy comparison is between price regulation and simple rewards. In other words, a key question for the planner is whether to structure a reward system which substitutes or complements intellectual property rights. The next proposition shows that condition (4), i.e., $B - \Pi^P \geq \varpi$, is a sufficient condition for price regulation to dominate simple rewards.

Proposition 6. *Price regulation can generate greater innovation incentives than simple rewards. When $B - \Pi^P \geq \varpi$, price regulation dominates simple rewards.*

Proof. See Appendix. □

The proposition highlights the channel through which the price regulation regime may generate greater welfare than simple rewards: stronger innovation incentives. Higher innovation incentives can be created by paying the same amount of cash as in a simple reward and but also letting the innovator enjoy monopoly rents from the patent in some of the periods. If the positive welfare effect generated by these greater innovation incentives dominates the negative effects of the dead-weight loss in the product market, price regulation that induces the use of the patent will strictly dominate the simple reward. In Section 6.1 we discuss this issue more in detail, and illustrate how these extra-incentives can be generated using a 'front-loaded' payment schedule.

The proof of the proposition also shows how the prize regulation regime can replicate a simple reward and thus achieve at least the same level of welfare when $B - \Pi^P \geq \varpi$. Intuitively, when $B - \Pi^P \geq \varpi$ the planner's budget is large enough to ensure that in each period the patent is kept dormant. In this case any reward with an expected payment that exceeds the total profits from the patent can be replicated with a price regulation scheme that transfers the same amount of money to the innovator and does not generate dead-weight loss.[4]

When $B - \Pi^P < \varpi$ simple rewards may be superior to price regulation in some environments. Consider, for example, the case in which ϖ is large and α is small so that (3) holds but $B - \Pi^P < \varpi$. In this case simple rewards can implement the first best but the planner's budget is not large enough to keep the patent dormant if a shock occurs. This implies that a price regulation regime generates a deadweight loss with some probability and cannot reach the first best welfare level.

Interestingly, this implies that the joint use of the two mechanisms (intellectual property and cash transfers) may be dominated by the use of only cash rewards. The intuition is that price regulation can always replicate a patent regime but can replicate a simple reward regime only if the planner's budget is large enough. When the planner does not have enough resources to convince the innovator to keep the patent dormant, the presence of the patent may reduce overall welfare.

When condition (3) is not satisfied, neither a simple reward regime nor a price regulation regime can generate the first best innovation investment. In this case, the welfare generated by a price regulation regime depends on the total amount of rewards promised to the innovator as well as on the timing of the payments. The next subsection explores this issue.[5]

6.1. Price regulation with limited budget

To develop some intuition about the role of the timing of the payment, consider the possible options available to the planner for the last reward, r_T. First, the planner may consider offering a schedule which keeps the *patent dormant in period T*. Such a schedule needs to satisfy both condition (4) and condition (5).

If (4) holds, the planner can use the following schedule r_{PR0} which satisfies (5) and transfers all the budget to the innovator:

$$r_T = \frac{B}{\delta^{T-1}}$$
$$r_t = 0 \text{ for } t = 1, \ldots, T-1.$$

With this schedule the expected reward for the innovator is

$$E(r_{PR0}) = B - \frac{1 - \widetilde{\delta}^T}{1 - \widetilde{\delta}} \alpha \varpi$$

which is the same as the expected payoff from a simple reward with the same schedule $r_{SR} = r_{PR0}$.

A second option for the planner is to design a schedule which induces the patentee to *use the patent in period T if a shock takes place*. In this case the last period reward will satisfy

$$\pi + \frac{\varpi}{\delta^{T-1}} \geq r_T \geq \pi.$$

[4] The proof of Proposition 6 focuses on simple rewards with payments exceeding Π^P. Rewards with payments lower than Π^P can be improved by a price regulation scheme that transfers Π^P to the innovator and does not generate dead-weight loss.

[5] The main results of our analysis hold if we compare optional rewards and price regulation regimes starting at period $\widetilde{t} > 1$. Comparing price regulation starting at period 1 with optional reward starting at a different period, $\widetilde{t}$, is more complex because price regulation generates monopoly distortions in the final periods of the technology life, whereas a delayed optional reward generates distortions during the initial periods. In this case delayed optional rewards may be preferred when the cost associated with anticipating the dead-weigh loss are compensated by the benefits of higher innovation incentives.

If (4) holds, the planner can use the following schedule $r_{PR\alpha}$ which transfers the entire budget to the innovator in the absence of shock, and keeps the patent dormant up to period $T-1$. In period T the patent will be used if a shock has occurred:

$$\begin{aligned} r_T &= \max\left\{\pi^P, \varpi\right\} \\ r_{T-1} &= \frac{B}{\delta^{T-2}} - \delta \max\left\{\pi^P, \varpi\right\} \\ r_t &= 0 \quad \text{for } t = 1, \ldots, T-2. \end{aligned}$$

With this schedule the expected payment for the innovator is

$$E(r_{PR\alpha}) = \begin{cases} B - \alpha \sum_{t=1}^{T} (1-\alpha)^{t-1} (\delta^{t-1}\varpi - \delta^{T-1}\pi^P) & \text{if } \varpi \geq \pi^P \\ B \text{ if } \varpi < \pi^P \end{cases}.$$

Notice that when $\varpi < \pi^P$ the forgone transfer at the last period is compensated by the rent obtained from the patent. This means that in this case the reward received by the innovator is not affected by whether a shock took place or not.

The third option for the planner is to design a reward schedule such that the patent is *always active in period T*, even when a shock does not take place. This can be implemented by a schedule which set $r_T = 0$. Notice that in this case the planner transfers less than the full budget because the left-over condition (2) requires saving some resources in case of a shock in the last period. If (4) holds, the planner can use the following schedule r_{PR1} to keep the patent dormant up to period $T-1$

$$\begin{aligned} r_T &= 0 \\ r_{T-1} &= \frac{B}{\delta^{T-2}} - \delta\varpi \\ r_t &= 0 \quad \text{for } t = 1, \ldots, T-2. \end{aligned}$$

With this schedule the expected payment for the innovator is

$$E(r_{PR1}) = B - \alpha \sum_{t=1}^{T} (1-\alpha)^{t-1} \delta^{t-1} \varpi + \delta^{T-1} (\pi^P - (1-\alpha)^T \varpi)$$

which can exceed the budget when ϖ is small. Intuitively, in period $T-1$ the planner can transfer a very large fraction of the budget to the inventor, leaving out only what is needed to deal with a shock at time T. If this amount is small the total payoff of the patentee can exceed the total budget of the planner.

It is important to notice how the schedules $r_{PR\alpha}$ and r_{PR1} involve the use of intellectual property (stochastically or deterministically) in the last period. In other words, these schedules display a *dynamic complementarity* of rewards and patents, in which the two instruments are active in different periods.

It is now natural to ask how the shape of the reward schedule affects welfare. Specifically, the planner may consider *back-loading* rewards to keep the patent dormant in the last periods or *front-loading* the rewards and let the innovator enjoy monopoly rents from the patent in the final periods. To understand the trade-offs shaping this decision, we focus on the case in which the planner has limited budget that does not allow implementation of the first best but can be used to keep the patent dormant for all T periods. In this setting, we compare the choice of keeping the patent dormant for T period (with the back-loaded reward schedule r_{PR0}) or letting the patent active in the final period (with the front-loaded reward schedule r_{PR1}). We obtain the following result.

Proposition 7. *If $\pi^P < (1-\alpha)^T \varpi$ back-loading the reward schedule generates greater welfare than front-loading the reward schedule.*

Proof. First notice that $E(r_{PR1}) - E(r_{PR0}) = \delta^{T-1}(\pi^P - (1-\alpha)^T \varpi)$ which is negative when $\pi^P < (1-\alpha)^T \varpi$. This implies that the back-loaded schedule r_{PR0} generates greater innovation incentives in this parameter range. This schedule also generates greater product market welfare because it avoids monopoly dead-weight losses. □

The above proposition implies that keeping the patent dormant generates greater social welfare when the monopoly profits are small relative to the resources that the planner needs to divert and when the likelihood of a shock is small. Specifically, the planner considers two elements. The first one, $\delta^{T-1}\pi^P$, is the extra rent the innovator obtains if the patent is active in the last period. The second one, $\delta^{T-1}(1-\alpha)^T \varpi$ is the fraction of the budget that will not be transferred to the innovator with a front-loaded schedule. This is because the planner needs to set resources aside in case there is a shock in the last period (according to the left-over condition 5) and these resources will not be transferred to the innovator to ensure that the patent is used. Contrasting these two elements implies that back-loading generates greater innovation incentives when the extra-rent that the active patent can generate is lower than the resources that are not transferred to ensure that the patent is active. The magnitude of the difference increases in δ. The final thing to notice is that when a back-loaded schedule generates greater innovation incentives, it also generates greater total welfare because it avoids the deadweight loss generated by the front-loaded schedule.

The planner may also consider a schedule that generates a stochastic patent in the last period, i.e., a patent which is actively used only if a shock occurs. In the next proposition, we compare the performance of this schedule with the one of front-loaded and back-loaded schedules.

Proposition 8. *Price regulation with a stochastic patent in period T: (i) generates higher welfare than a front-loaded schedule when* $\varpi > \pi^P$ *(ii) generates higher innovation incentives than a back-loaded schedule.*

Proof. To see part (i) notice that when $\varpi \geq \pi^P$

$$E(r_{PR\alpha}) - E(r_{PR1}) = \delta^{T-1}(1-\alpha)^T\left(\varpi - \pi^P\right) > 0.$$

Because $r_{PR\alpha}$ stimulates more innovation incentives than r_{PR1}, it also generates greater welfare because the deadweight loss is only stochastic. Part (ii) follows from $E(r_{PR\alpha}) - E(r_{PR0}) =$

$$\frac{1-(1-\alpha)^T\delta^T}{1-(1-\alpha)\delta}\alpha\varpi \quad \text{if } \varpi < \pi^P$$

$$\pi^P\alpha\delta^{T-1}\frac{1-(1-\alpha)^T}{1-(1-\alpha)} \quad \text{if } \varpi \geq \pi^P$$

which is positive in both cases. □

The main difference between a stochastic patent and a front-loaded schedule is what happens if the shock does not take place. First, with a front-loaded schedule there is a deadweight loss in the product market that is avoided with the stochastic patent. Second, relative to a stochastic patent, a front-loaded schedule allows the innovator to receive the monopoly rent π^P but at the cost of giving up the left-over resources in the planner's budget, ϖ. When $\varpi > \pi^P$ the total rent received by the innovator is larger with a stochastic patent. Together, these two features imply that total welfare is greater with a stochastic patent when $\varpi > \pi^P$.

The welfare comparison between the stochastic patent and the back-loaded schedule is less straight forward. On one hand innovation incentives are always larger with the stochastic patent as shown in part (ii) of proposition 8. This follows because in the absence of a shock the planner transfers the same amount of funds as with the back-loaded schedule and in the presence of a shock compensates the lower transfer due to the diverted resources with monopoly rents. On the other hand, in the presence of a shock the stochastic patent generates a deadweight loss in the product market which is not present with the back-loaded schedule. Building on these insights, the next proposition identifies conditions under which a front-loaded schedule, which displays dynamic complementarity between rewards and patents, generates the largest welfare.

Proposition 9. *A front-loaded schedule generates the largest total welfare when* $\pi^P - \varpi$ *is positive and large, l is small and p′ is large.*

Proof. First, $\pi^P > \varpi$ also implies $\pi^P > (1-\alpha)^T\varpi$ so the front-loaded schedule generates greater innovation incentives than the back-loaded schedule. Moreover, when $\pi^P > \varpi$

$$E(r_{PR\alpha}) - E(r_{PR1}) = \alpha\sum_{t=1}^{T}(1-\alpha)^{t-1}\delta^{t-1}\varpi - \delta^{T-1}(\pi^P - (1-\alpha)^T\varpi)$$

which is negative when $\pi^P - \varpi$ is large enough so the non-stochastic patent generates more innovation effort. When the difference in product market between having or not a patent is small (small l) but innovation effort increases a lot with extra-rents (p' is large) the non-stochastic patent dominates. □

Proposition 9 describes features of the environment in which a dynamic mix of rewards and patents through a front-loaded schedule is optimal. First, notice that when $\varpi < \pi^P$ the resources required to keep the patent dormant exceed those required to meet the financial needs of a shock. This implies that by front-loading the reward the planner can offer the innovator greater R&D incentives than by back-loading the reward and try to keep the patent dormant. In fact, in this case the overall reward of the innovator (transfer received by the planner plus monopoly profits in period T) may actually exceed the total budget available to the planner and generate large innovation incentives, especially when p increases steeply. At the same time, the cost of having a patent in the last period is the dead-weight loss, l, generated in the product market. When l is small and p' is large, this welfare loss is compensated by the welfare gain.

Crucially, proposition 9 shows that in these environments a *dynamic complementarity* between prizes and patents arises. By using cash prizes to avoid dead-weight losses only in some periods, the planner can increase the rent and the R&D incentives of the innovator relative to the case in which all dead-weight losses are avoided. To develop the intuition for this result, consider a reward schedule keeping the patent dormant for T periods. Innovation incentives can be increased by transferring the same amount of cash to the innovator during the first $T-1$ periods and let the innovator enjoy monopoly profits in period T. These higher innovation incentives represent the benefits of the joint use of patents and prizes. On the other hand, the cost of the complementary use of the two tools is the dead-weight loss in the last period. Proposition 9 describes environments in which the cost is outweighed by the benefits.

7. Diverting resources toward low-welfare investments

Our baseline model assumed that the net welfare generated by the alternative investment, λ, was large enough that the planner would always want to invest immediately if the opportunity arises. This is equivalent to assuming that λ is very large relative to l. In such environment it was natural to restrict the planner to use schedules satisfying the left-over condition (2), which assured that in each period i the planner had enough resources to pay for the alternative investment in case the shock took place in future periods.

This section extends our analysis considering the case in which λ is not necessarily large relative to l. In examining this case, we do not restrict the planner to save resources to pay for the alternative investment and allow instead for the possibility of trading-off the distortion from dead-weight loss with the welfare generated from the alternative investment.

To provide a sharper intuition of why results may differ when λ is small, we focus on a simplified version of our baseline model. Specifically, we consider the case in which $\tau = \varpi$, $T = 1$ and $\alpha = 1$. In this simplified environment, there are only two periods (one for innovation investment and one for market interaction), and the total resources available to the planner, τ, can be used to generate welfare λ only if the entire budget is spent on the alternative project. By setting $\alpha = 1$ we assume that the alternative investment does not arise stochastically, but happens with certainty at $T = 1$. These assumptions simplify dramatically the analysis but are not crucial for the key insights, as we discuss at the end of this section.

In this environment a patent system generates welfare equal to

$$W^P = p(k(\pi^P))[s^* - l] - k(\pi^P) + \lambda.$$

The simple reward regime performs very poorly in this simplified model because the government cannot commit to the prize and $\alpha = 1$. To see this, assume that the planner announces a prize equal to s^*. At the time of payment, the government will compare the (ex-post) welfare from paying the prize with the welfare from diverting the resources to the alternative project. If the reward is paid to the innovator, the product market welfare will be s^*. Notice, though, that at the moment of payment the innovation is in the public domain and payment of s^* has no effect on the product market. Therefore, the welfare from diverting the budget to the alternative project is $s^* + \lambda$. This implies that for every $\lambda > 0$ the government will not pay the reward. The innovator will anticipate not being paid, and will not invest in innovation. In other words, because the commitment problem is extremely severe ($\alpha = 1$) simple prizes are completely ineffective and, thus, dominated by patents. Hence, we have the following:

Remark 10. $k = 0$ for any simple reward r. Patents generate greater social welfare than prizes.

Consider now the optional reward regime where the innovator can choose between a reward r and a patent. First, notice that optional rewards are equivalent to price regulation in this simplify setting because $T = 1$. Second, notice that the innovator will choose the reward only if $r \geq \pi^P$. At the time of the payment, the planner compares the welfare from buying the patent and the welfare from diverting the budget to the alternative project. Because the innovator owns the patent, diverting the resources affects product market outcomes. More precisely, the product will be sold in a competitive market if the patent is bought-out generating product market welfare s^*. In the absence of buy-out the product will be sold in a monopoly market generating product market welfare equal to $s^* - l$. This implies that the planner will divert resources to the alternative project only if $\lambda > l$. We have the following:

Proposition 11. *In the optional reward system, innovation incentives and welfare are equal to those of the patent system if $\lambda > l$ and larger than those of the patent system if $\lambda \leq l$. Welfare is below the first best level for any $\lambda > 0$.*

Proof. The welfare generated with the patent system is equal to W^P. When $\lambda > l$, the innovator anticipates that no reward will be paid and she invests as in the patent system. When $\lambda \leq l$ and there is a reward r the corresponding total welfare will be

$$p(k(r))(s^* - \lambda) - k(r) + \lambda. \tag{6}$$

Let us define $\Delta \equiv s^* - \lambda$ and set $r = \Delta$. We have

$$p(k(\Delta))\Delta - k(\Delta) + \lambda \geq p(k(\pi^P))\Delta - k(\pi^P) + \lambda \geq W^P$$

where the first inequality follows from profit maximization and the second one from $\lambda \leq l$. Finally notice that $r = s^* - \lambda \geq s^* - l \geq \pi^P$. □

The proposition shows that in the optional reward system the presence of the patent helps the government committing to pay the reward, and this increases innovation investments and welfare relative to simple rewards and patents. When the welfare generated by the alternative investment is large ($\lambda > l$) the optional reward regime guarantees the innovator monopoly profits and therefore stimulates a positive innovation investment. When the welfare generated by the alternative investment is more modest ($\lambda \leq l$) the planner will forego the alternative opportunity to maximize product market welfare. The innovator will anticipate this behavior and invest efficiently in R&D.

This simple extension of our baseline model shows, in the case when $\lambda \leq l$, a *static complementarity* between the two policy instruments generated by the commitment problem, which differs from the *dynamic complementarity* discussed in Section 6.1. Through the cash prize the planner can reward the innovator transferring rents which are larger than monopoly profits, and this stimulates more R&D investment than patents. Cash rewards also have the beneficial effect of removing deadweight loss distortions in the product market. At the same time, when the innovator owns a patent, the incentives for the planner to divert resources away from the cash prize are reduced. This is because reneging on a cash prize has no impact on product market welfare once the innovation has been developed. Conversely, in the presence of patent rights, reneging the reward generates a deadweight loss in the product market which reduces the planner's incentives to divert resources. The superior performance of the optional reward system is consistent with the view of Roin (2014) that patents can act as a discipline device for government rewards.

The simplified model analyzed in this section focused on the case in which the shock was non-stochastic and the budget of the planner had to be entirely directed toward the alternative investment. If the opportunity to invest in the alternative project arises with probability α simple rewards may perform better, and even implement the first best with $r = s^*/(1-\alpha)$ if $\tau \geq s^*/(1-\alpha)$. This is consistent with the analysis of our baseline model that showed how simple rewards can perform relatively well when the commitment problem is not very severe (α is small) and the government does not face a strong budget constraint (large τ). As the budget becomes more limited and the commitment problem more severe, prizes become less effective and dominated by patents and optional rewards. More importantly, the incentive to divert resources to low welfare opportunities ($\lambda \leq l$) is reduced in an optional reward system even in the presence of stochastic shocks, because monopoly distortions are generated when the planner reneges on the payment.

Extending the model to $T > 1$ periods would also not affect the key insight of proposition 11, as avoidance of product-market dead-weight losses may induce the planner to forego alternative investments also in this case. With $T > 1$ the equivalence between optional rewards and price regulation no longer holds, and price regulation has the potential to generate larger innovation incentives as we discussed in Section 6.

8. Concluding remarks

Traditionally, the innovation policy literature has viewed cash rewards and patents as substitute tools to encourage research investments. Our theoretical framework shows that, in the presence of commitment issues, complementarities may arise and the joint use of the two tools may generate greater welfare. Counterintuitively, in settings where patent rights generate large dead-weight losses, their beneficial role as discipline device is greater. At the same time, our analysis suggests that the joint use of the two tools may not be appropriate when the planner's budget is limited. In this case the cash resources can only partially avoid product market distortions and this reduces the beneficial disciplining effect of patents. In this case, simpler innovation prizes with patents in the public domain may be preferable to more complex policies.

More broadly, our paper provides support to the idea that information frictions are only one of the key trade-offs that should be considered in comparing innovation policy tools and that in various technological environments the joint use of multiple policy instruments may be more effective than the implementation of simple policies.

Our theoretical results have implications for innovation policy and can provide guidance to government agencies and philanthropists on how to design effective innovation prizes. Specifically, our analysis suggests that the efficacy of an innovation policy tool may crucially depend on the commitment of the agency implementing the policy. In the public sector, concerns over commitment are likely to arise in times of tight budgets or in periods of geopolitical instability. In the private sector, commitment issues may be present with new philanthropists or private firms organizing innovation prizes that do not have an established reputation.

Declaration of Competing Interest

None.

Appendix A. Omitted proofs

Proof of Proposition 1. Consider a schedule r_{SP} implementing the first best. If this is a credible schedule, such as $r_{SP} = (s^*, \ldots, s^*)$, then it has to satisfy $B - \varpi \geq R$ and $R = S^*$ which imply $B - (1 - \widetilde{\delta}^T)\alpha\varpi/(1-\widetilde{\delta}) \geq S^*$. Consider now the case in which the schedule is risky. To implement the first best, total payment R must satisfy

$$S^* = (1-\alpha)^T R + \alpha \sum_{t=1}^{T} (1-\alpha)^{t-1} \min\left\{B - \delta^{t-1}\varpi, R\right\}.$$

The maximum transfer to the innovator takes place when $R = B$ and in this case $\min\left\{B - \delta^{t-1}\varpi, R\right\} = B - \delta^{t-1}\varpi$ for every $t \geq 1$. This implies that for a risky schedule implementing the first best we have

$$\begin{aligned} S^* &= (1-\alpha)^T R + \alpha \sum_{t=1}^{T} (1-\alpha)^{t-1} \min\left\{B - \delta^{t-1}\varpi, R\right\} \\ &\leq (1-\alpha)^T B + \alpha \sum_{t=1}^{T} (1-\alpha)^{t-1} (B - \delta^{t-1}\varpi) \end{aligned}$$

which leads to

$$S^* \leq B - \frac{1-\widetilde{\delta}^T}{1-\widetilde{\delta}} \alpha \varpi .$$

To see the "if" part of the proof start with the case in which $B - \varpi > S^*$. In this case the credible schedule $r_{SP} = (s^*, \ldots, s^*)$ can implement the first best. Consider now the case in which $B - \varpi \leq S^*$. In this case we can construct a schedule that is paid in full only when no shock occurs. To implement the first best this schedule needs to satisfy

$$S^* = (1-\alpha)^T R + \alpha \sum_{t=1}^{T} (1-\alpha)^{t-1} (B - \delta^{t-1} \varpi)$$

or

$$R = \frac{S^* - \alpha \sum_{t=1}^{T} (1-\alpha)^{t-1} (B - \delta^{t-1} \varpi)}{(1-\alpha)^T}.$$

This schedule can be constructed only if

$$B \geq \frac{S^* - \alpha \sum_{t=1}^{T} (1-\alpha)^{t-1} (B - \delta^{t-1} \varpi)}{(1-\alpha)^T}$$

which can be re-written as

$$S^* \leq B - \frac{1-\widetilde{\delta}^T}{1-\widetilde{\delta}} \alpha \varpi .$$

Proof of Proposition 6. We first show that when $B - \Pi^P \geq \varpi$, price regulation dominates simple rewards. Consider a simple reward such that $E(r_{SR}) \geq \Pi^P$. If r_{SR} is credible we have that $E(r_{SR}) = R \geq \Pi^P$. In this case a price regulation regime with $r_T = R/\delta^{T-1}$ and $r_t = 0$ for $t = 1, \ldots, T-1$ can replicate the outcome of the simple reward. In fact, the schedule transfers the innovator R and this generates the same innovation incentives of the simple reward. Moreover, $R \geq \Pi^P$ implies that the patent remains dormant for the entire T periods, so there is no dead-weight loss in both regimes. If r_{SR} is risky we have that

$$E(r_{SR}) = (1-\alpha)^T R + \alpha \sum_{t=1}^{T} (1-\alpha)^{t-1} \min\left\{B - \delta^{t-1} \varpi, R\right\}.$$

Also in this case a price regulation regime with $r_T = R/\delta^{T-1}$ and $r_t = 0$ for $t = 1, \ldots, T-1$ can replicate the outcome of the simple reward. In fact, the schedule transfers the innovator $E(r_{SR})$ and this generates the same innovation incentives of the simple reward. Moreover, because $B - \delta^{t-1}\varpi \geq \Pi^P$ for all $t \geq 1$, also in this case the patent remains dormant for the entire T periods, so there is no dead-weight loss in both regimes.

To see how price regulation can generate greater innovation incentives than simple rewards even if $E(r_{SR}) \geq \Pi^P$, consider now a price regulation regime with $r_t = 0$ for $t = 1, \ldots, T-2$, $r_{T-1} = R/\delta^{T-2}$ and $r_T = 0$. This schedule keeps the patent dormant up to $T-1$, but the inventor will use the patent at time T. In this case, the expected profits for the innovator will be

$$(1-\alpha)^{T-1} R + \alpha \sum_{t=1}^{T-1} (1-\alpha)^{t-1} \min\left\{B - \delta^{t-1} \varpi, R\right\} + \delta^{T-1} \pi^P$$

which exceed those of the simple reward. So the price regulation regime has the potential to generate greater innovation incentives than a simple reward by combining cash transfers and monopoly rents. If the positive welfare effect generated by these greater innovation incentives dominates the negative effects of the dead-weight loss in the product market, price regulation strictly dominates simple rewards.

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