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Forward Markets to Spur Innovation

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Abstract

This paper presents a mechanism inducing costly research and innovation in the absence of intellectual property rights. The mechanism relies on forward contracting between the provider of the innovation and firms or individuals that benefit from the pecuniary effects of the innovation, rather than from its direct use. Applied to innovation as a non-discrete public good, the mechanism resolves time consistency, agency, and free-riding problems, and provides an incentive for *ex post* efficient pricing.

Key words

innovation, public goods, mechanism design, patents, forward contracts

1. Introduction

Innovation presents a quandary. A firm that provides such a public good cannot exclude non-payers from using it. If a consortium or public entity solves the collective action problem and sponsors research, agency problems appear. R&D activities are typically unverifiable, and an R&D firm is likely to have private information about a project's costs and benefits, causing inefficiency and moral hazard.

Patents can sometimes solve these problems, but come with the anti-commons: inefficiently high prices, inadequate diffusion, and a reduction in subsequent innovations. This paper offers a different mechanism, building on the literature on the private provision of public goods and the insights of Allen (1983) and Hirshleifer (1971) on profiting from the pecuniary effects of an innovation. Our mechanism has a firm which provides an innovation profit not from selling the good, but from engaging in financial transactions that are profitable when the innovation changes the price of other assets. In some conditions, the mechanism solves the free-rider and agency problems of contracted research, and the monopoly problems of the patent system.

Successful innovations disrupt markets, changing the prices of assets. A case in point is blast furnace innovation in England's Cleveland District in the nineteenth century (Allen 1983). The iron smelters, who owned both furnaces and iron ore mines, aggressively invested in innovation

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and apparently allowed unrestricted access to the advances in smelting technology. By sharing the new technology, smelters greatly increased smelting productivity, and with it the value of their iron ore holdings. That appreciation appears to have constituted the returns to innovation for the inventors.

Forward contracts allow the smelters' solution to be generalized. For example, suppose a firm develops an innovation that reduces the cost of avoiding greenhouse gas emissions but neither uses the innovation itself nor owns related assets. In a cap-and-trade system and in the absence of intellectual property rights, the new technology reduces the market price of pollution permits to the new marginal abatement cost. Thus, firms that pollute and that are required to have pollution permits will benefit from the innovation; and firms buying the new, cheaper, abatement technology also benefit. In our mechanism the inventor sells contracts to polluters for future pollution permits. If the R&D firm innovates, the spot price for permits in the future declines and the R&D firm realizes a profit.

Our mechanism applies when the price of the related good, or target asset, either rises or falls. Consider a carbon tax, and suppose the R&D firm works on a carbon capture and sequestration technology. Successful innovation would increase the price of coal, as electricity generators would no longer need to pay a carbon tax on emissions from coal-generated electricity, and demand for coal will rise. The R&D firm would transact with coal producers, agreeing to buy coal at a future date for a price that is higher than the current price of coal, but lower than the price that would prevail should the innovation succeed. In all of these cases, the R&D firm has an incentive to promote wide diffusion and use of the invention.

An equilibrium with investment by the R&D firm requires that it profit from investing after it sells forward contracts, and that the asset users profit from buying forward contracts. For expected profits of the R&D firm to be non-negative, the price of a forward contract must exceed the expected spot price for future purchases of the asset, as the firm must, at a minimum, cover both its R&D expenses and the expected cost of fulfilling its forward contract obligations. A risk-neutral asset user, however, will profit from buying forward contracts only if the price of a forward contract is no greater than the expected price of the asset in the spot market in the following period. These two conditions, one for the R&D firm, and one for the asset users, appear contradictory. But they are consistent, if by buying a forward contract an asset user induces the R&D firm to invest in R&D, whereas foregoing the (last) contract means the R&D firm conducts no research. In other words, the price of the future contract for an asset user needs to be lower than the expected spot price under no R&D, whereas the price for the R&D firm needs to exceed the expected spot price in the presence of R&D. Thus, it is critical that each asset user's purchase of forward contracts be decisive – any reduction in its purchase below the equilibrium level will stop the R&D firm from investing.

A well-known solution to free-riding in the provision of public goods makes each contributor decisive, in the sense that absent his contribution the good is not provided (Palfrey and

Rosenthal, 1984). These models have two critical assumptions. First, to support decisiveness of an individual donor the good must be discrete. Second, once funded, the charitable organization delivers the public good as promised, or, alternatively, it is provided by the sponsors themselves. Though our mechanism relies on the same requirement for decisive asset users, the sale of enforceable forward contracts relaxes both assumptions. Rather than soliciting contributions, the R&D firm sells forward contracts at a specified price, with the proviso that it will accept the contracts only if their number meets some specified minimum level. This offer resembles a tender offer for company shares, which is activated only if enough shares are tendered. The R&D firm can set the price of the contract low enough so that it earns non-negative profits only if the tender offer is satisfied: any fewer sales and the firm would suffer an expected loss. The forward contracts thus establish a credible commitment for the tender offer, and the specified participation level becomes a threshold. Furthermore, the contracts resolve agency problems: if the R&D firm shirks, it will suffer expected losses when the forward contracts come due.

We show that this mechanism supports a subgame perfect Nash equilibrium with high investment in R&D. The mechanism works even when all actors are risk neutral and all information is shared; it is not based on speculation by an informed inventor. Asymmetric information in part weakens and in part strengthens the mechanism. The existence of any equilibrium with positive investment requires a certain level of expected pecuniary benefits; with asymmetric information, the minimum level increases. The R&D firm can, however, exploit its private information to allocate a greater share of the benefits to itself rather than to its contractees, which is useful when the R&D firm has pre-contractual sunk costs associated with the project.

The next section discusses related literature. Sections 3 and 4 present our basic model. Knife edge result ... Section 5 generalizes it to the R&D firm having private information about the cost or likely success of the proposed project. Section 6 concludes.

2. Literature

Economists have proposed many alternatives to patents. Most closely related to this mechanism are the proposals that address agency issues.[3] In an influential paper, Wright (1982) questions the need for any patent system, suggesting that the government (or other entity providing a public good) can establish a prize that solves agency problems without an anti-commons intellectual property right. An innovation prize famously supported the development of a sea-worthy longitude measure, and today gives incentives for research on vaccines, high-efficiency cars, basic science, and space travel. (Kremer and Williams, 2010)

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[3] Other alternatives are discussed in Moser (2005) who analyzes innovative activities in 19th century European countries that lacked formal intellectual patent rights; Powell and Giannella (2010) on collective innovation; and Von Hippel on open asset user innovation (2010). Formal mechanisms based on procurement contracts that resolve information asymmetry but not the agency problems related to verifiability are explored in Scotchmer (1999a, 1999b) and Saloner(1982).

The use of innovation prizes is limited by the need to define the terms of the award, and hence the specific characteristics of the technology. Whether this requirement is problematic varies. In general, prize-qualifying inventions are easier to identify for technological and scientific advances, and more complicated when an innovation is intended to be commercial, as both cost and technical prowess factor into its success. Alternatively, the mechanism using forward markets relies on diffusion and sales to induce pecuniary effects. It thus complements the prize mechanism in addressing commercial rather than scientific advances.

The Advanced Market Commitment (or AMC; Kremer, 1998) is another patent alternative. Geared at inventions such as tropical medicines whose social value exceeds their private value, a sponsor such as the World Health Organization or the Gates Foundation contracts a price in advance with R&D firms for the *ex post* purchase of a fixed number of doses. As with the forward-market mechanism, the R&D firm has incentives to invest in both innovation and diffusion and bears risks of success and failure.

A key distinction between an AMC and the forward-market mechanism is that the AMC contracts on the technology itself, whereas the forward-market mechanism contracts on the effects of an innovation on the price of an asset. Contracting on such externalities can be useful. The goods or services whose price may change with innovation exist, and their current cost and price is known. The innovation, alternatively, does not. Furthermore, a range of options may result in a relevant innovation. For example, the R&D firm could sign forward market contracts with the agencies that treat malaria victims, based on the budget savings of the agencies should a successful vaccine be developed. The R&D firm would have an incentive to invest in any activity that would reduce the disease incidence or severity. Should the vaccine project fail, the firm could change its research direction without need for a complex contingent contract or renegotiation.

The seminal work showing how an inventor can profit from changes in the price of associated goods is Hirshleifer (1971). He suggests that an innovator with private information can profit from the price changes his innovation induces and has an incentive to innovate even if afforded no patent protection. Eli Whitney, for example, frustrated in his efforts to profit from his cotton gin patents, should instead have speculated in cotton-bearing land or in the price of cotton. Of course these incentives are not unique to research programs. Speculating on private information provides general incentives to invest. An example of profitable speculation in assets appears with the development of trolley lines. Railroad entrepreneurs in southern California in the early 1900s made their profits not from revenue from the trolley lines they built, but from buying land along the route of the trolley before the line was built from uninformed land-owners, and then subsequently selling that land at high prices (Sheehan 1982).

Hirshleifer’s proposal rests on the innovator/speculator keeping information private while he speculates, which requires that market prices not immediately adjust to the new equilibrium. Financial markets can help. Sufficient conditions for a speculation-based mechanism to induce innovation include the presence of a market in forward contracts,[4] which allows the inventor to speculate in private, and the existence of private demand shocks for hedgers, so that they cannot infer whether the price of a futures contract reflects transactions by the speculator or shocks to the state of nature (Cohen and Glazer 2012).

The forward-market mechanism discussed here allows R&D to be risky, but does not require any secrecy or private information: all information, including the likelihood that the R&D investment will succeed, can be common knowledge at the time of contracting, thereby loosening the restrictions in the speculation-based policies. For example, by not requiring individual demand shocks, the mechanism we discuss could work for an innovation in gas drilling technology, based on gas forward contracts, even if demand-based shifts in the futures price of gas are observed or identically experienced by all firms trading in forward contracts. Furthermore, the mechanism does not require well-developed futures trading exchanges: it can be supported by either a futures market or a forward market, based on contracting outside a formal trading exchange.

The value of forward trading to establish commitments has been studied in other contexts. For example, Mahenc and Salanie (2004) show that forward markets can enable duopolists to commit to higher spot market prices. Under alternative assumptions about oligopolistic behavior, strategic use of forward markets can lower prices (van Eijkel and Moraga-Gonzalez 2012). Laffont and Tirole (1996) consider how a government can issue options for future pollution permits to commit itself to second period permit prices that do not undermine the patent rights of private inventors.

We consider how forward contracts allow an R&D firm to commit, both to establish time consistency for the tender offer, and to create incentives to perform. The mechanism depends on finding a forward contract that is attractive *ex ante* to both the R&D firm and to the asset users, as is explored in the following sections.

3. Definitions and Assumptions

Asset users

Let there be *N* firms which use an asset whose price is affected by new technology. We call this asset the *target asset*, and consider the case where its price will drop with innovation (the reverse case is symmetric). These *N* firms thus stand to gain pecuniary benefits from the innovation, and we call them *asset users*. The asset users can, but need not, be users of the innovation. For example, the innovation may reduce carbon emissions by generating plants using coal. Under a cap-and-trade policy, these reduced emissions cause the spot price of carbon permits to drop,

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[4] Markets in which traders can anonymously buy or sell contracts for future delivery of commodities are usually called "futures markets", and the contracts are "futures contracts". Forward markets and forward contracts can take this form, but can also be bilateral contracts between known parties for future delivery of an asset or commodity.

thereby benefiting producers of cement, who gain no direct benefit from the new technology, but who now buy carbon permits at the lower price. The target asset is a pollution permit, and the cement manufacturers, as well as any other entity that holds permits for emissions, are the asset users.

For simplicity, we suppose that demand for the target asset is inelastic. Our results hold under a standard formulation of demand, which would add notation but no insights to this analysis. Each asset user uses B_i units of the asset; in total, asset users demand $B = \sum_{i=1}^{N} B_i$ units. The asset users can buy the target asset on the spot market in period 3, or buy forward contracts in period 1 for units to be delivered in period 3. If sufficient forward contracts are executed, the R&D firm conducts research in period 2. Asset user i buys b_i forward contracts and $(B_i - b_i)$ spot market units of the asset. We ignore any temporal discounting and assume all firms are risk neutral.

The innovator

One firm, called the R&D firm, can invest in innovation. The firm is risk-neutral, aiming to maximize expected profits. The R&D firm issues a tender offer $T = (\hat{f}, \hat{b})$, specifying that it will sell forward contracts at a price of $\hat{f}$ per unit if and only if the number of contracts bought is $\hat{b}$ or more, with $0 \leq \hat{b} \leq B$.

If the forward contracts are executed, the R&D firm chooses to spend x on innovation. It innovates with probability $R(x)$, which is increasing in x and exhibits diminishing marginal returns to investment. If the R&D firm innovates, then the market price of the target asset in period 3 is zero. Otherwise the market price of the asset is $p > 0$. In period 3, the R&D firm buys units of the target asset on the spot market to cover forward contracts.

Financial benefits

The financial benefit of the investment is the reduction in the asset price. The expected total financial or pecuniary benefit when investment is x is $R(x)Bp$. A necessary condition for this mechanism to induce R&D is that the expected pecuniary benefits suffice to cover R&D expenses for some level of R&D investment:

Assumption A: Some positive investment level x satisfies, $x \leq R(x)Bp$.

The collective action problem is interesting when asset users are subject to a prisoners' dilemma. As we show below, both the forward contract price and the expected spot price decline with the sale of additional forward contracts. We assume that asset users are small enough that they cannot justify the marginal purchase of forward contracts on the basis of individual benefits:

Assumption B: Let $b \geq \hat{b}$. Then $\frac{d[f b_i + (1-R)p(B_i - b_i)]}{d b_i} > 0 \ \forall\, i = 1, \dots, N$.

Information

We initially assume perfect information. All asset users and the R&D firm know the function $R(x)$, and each asset user knows the total subscriptions bought by all other asset users.

Timeline

The model posits three stages: a contracting stage, an investment stage, and a payoff stage. The timeline is as follows:

Period 1 (contracts)

1.1 The R&D firm issues a tender offer $T = (\hat{f}, \hat{b})$, specifying the minimum total subscription in the project, $\hat{b}$, and the price of a forward contract, $\hat{f}$, with $0 \leq \hat{b} \leq B$.

1.2 Asset user i offers to buy b_i forward contracts at price $\hat{f}$ per unit.

1.3 If $\sum_{i=1,..,n} b_i = b \geq \hat{b}$, then the R&D firm sells b forward contracts. Otherwise it does nothing.

Period 2 (investment)

2.1. If the forward contracts are executed, the R&D firm chooses the profit-maximizing level, x^*, of its spending on R&D.

Period 3 (payoffs)

3.1. The R&D firm innovates with probability $R(x^*)$.

3.2. The R&D firm buys the asset on the spot market to fulfill its forward contracts, and realizes its profits. If the R&D firm innovated, the price of a unit of the asset in period 2 is 0; otherwise the price is $p>0$.

4. Equilibrium behavior

We investigate a symmetric equilibrium where all asset users take identical actions. The equilibrium is a hybrid. The first two periods are subgame perfect: in period 1 the R&D firm proposes a tender offer and, if accepted by the asset users, abides by it in period 2, investing in research if and only if the tender offer is satisfied. The asset users buy forward contracts so as to satisfy the tender offer; none of them unilaterally diverge. Period 3 actions are governed by enforceable contracts. At that time, some of the parties may wish to dishonor their commitments, but are precluded from doing so by an external enforcement mechanism.

An equilibrium tender offer must give the R&D firm an incentive to invest in R&D, and an incentive for the asset users to buy forward contracts in the amount of the tender. Moreover, if the equilibrium is subgame perfect, the R&D firm must accept the offers to buy contracts only when the totality of the offers exceeds the tender. These considerations are explored below. The equilibrium outcome is determined by working backwards.

Profits of the R&D firm when it sold forward contracts and invested

The R&D firm's profits when it is successful are the proceeds from the sale of forward contracts minus spending on R&D. When the R&D fails, the R&D firm must in addition buy the assets to cover the forward contracts. The expected profits of the R&D firm, conditional on a tender offer $T = (\hat{f}, \hat{b})$, sales of forward contracts b, and investment x are:

(1) $$E(\pi) = R(x)\hat{f}b + (1 - R(x))(\hat{f}b - pb) - x = \hat{f}b - (1 - R(x))pb - x.$$

Profit-maximizing spending by the R&D firm when it sold forward contracts

The first-order condition for profit-maximizing spending on R&D is:

(2) $$\partial E(\pi) / \partial x = R'(x)pb - 1 = 0 \;\;\rightarrow\;\; R'(x) = \frac{1}{pb}.$$

Equation (2) determines the investment x for each value of b, or a function $x^*(b)$ where

(3)
$$\frac{dx^*(b)}{db} = -p\frac{[R'(x)]^2}{R''(x)} > 0.$$

Note that though the R&D firm's investment depends on b, the investment does not depend on the price of a forward contract $\hat{f}$. The R&D firm gets the revenues from the sales of contracts whatever it later spends on R&D. In choosing its spending on R&D, the R&D firm considers how many units of the asset it may have to buy on the spot market, and the price of the asset should its R&D fail.

The tender offer

We next consider the contracting stage. If the R&D firm sells forward contracts if and only if the subscription level b is at least the tender offer $\hat{b}$, then the R&D firm must have positive expected profits for $b \geq \hat{b}$ and negative expected profits for $b < \hat{b}$ given the forward contract price $\hat{f}$. Furthermore, if the R&D firm spends money on R&D (performs on the contracts), then it must expect to lose money if it simply keeps the revenue from sale of forward contracts, does no research, and covers the contracts in the spot market. Proposition 1 describes tender offers T satisfying these conditions:

Proposition 1: Let $T = (\hat{f}, \hat{b})$ be a tender offer such that

(4.1) $$\hat{f} = \left(1 - R\left(x^*(\hat{b})\right)\right)p + \frac{x^*(\hat{b})}{\hat{b}}$$

and

(4.2) $\left(1 - R\left(x^*(\hat{b})\right)\right)\hat{b}p + x^*(\hat{b}) = \hat{f}\hat{b} \leq p\hat{b}$

where $x^*(\hat{b})$ is defined by equation (3). Then the R&D firm will sell contracts and engage in R&D if and only if $b \geq \hat{b}$.

(See the appendix for all proofs.)

Equation (4.1) establishes the credibility of the tender offer. It states that the forward contract price equals the expected asset price when $\hat{b}$ forward contracts are sold, plus a share of the R&D cost. If precisely $\hat{b}$ assets are sold, the R&D firm will, in expectation, exactly cover its costs, and have zero profits. As proved in the Appendix, expected profits for the R&D firm increase monotonically in *b*, holding $\hat{f}$ constant. Thus, the R&D firm is unwilling to sell forward contracts at a price $\hat{f}$ for any quantity less than $\hat{b}$, so that when the participation level is exactly $\hat{b}$ each asset user is decisive. Equation (4.1) clarifies the role of the forward contract price: it restricts the R&D firm's expected profits so that the tender offer is credible.

Equation (4.2) further restricts the tender offer to establish research credibility. The left-hand side of the equation is the revenues from sales of $\hat{b}$ forward contracts. The R&D firm performs R&D if and only if this value is less than the cost of covering those contracts on the spot market when no R&D is performed. If the firm does conduct research, it expects to merely break even, whereas if (4.2) is not satisfied, the firm does better by keeping the revenue from sales of forward contracts and conducting no research. Equation (4.2) can be rewritten as:

(5) $\left(1 - R\left(x^*(\hat{b})\right)\right)p + \frac{x^*(\hat{b})}{\hat{b}} \leq p \rightarrow x^*(\hat{b}) \leq p\hat{b}R\left(x^*(\hat{b})\right)$.

Thus, a requirement for a tender offer to be time consistent is that the R&D firm's spending on R&D not exceed the expected financial benefits from the innovation associated with the asset units for which forward contracts were made.

Equation (5) may not hold for small values of *x*. Suppose the R&D firm sells only one forward contract, including in its price the entire cost of the R&D program. Depending on *R(x)*, the R&D firm might well prefer to simply keep that money and buy a unit of the asset on the spot market to cover the sole contract. The condition places a lower bound on the number of forward contracts that must be sold:

Proposition 2. If there exists a feasible subscription level $\underline{b}$, where $0 < \underline{b} \leq B$ and

$$x^*(\underline{b}) = p\underline{b}R(x^*(\underline{b})).$$

Then for all $\hat{b}$ such that $\underline{b} \leq \hat{b} \leq B$,

$$x^*(\hat{b}) \leq p\hat{b}R(x^*(\hat{b})).$$

Profit-maximizing purchases of forward contracts by asset users

Consider next the decision of an asset user buying forward contracts. Note first from equations (2) and (3) that $x^*(b)$ increases with b and that $R(x)$ increases with x. Increased participation by asset users induces the R&D firm to increase investment. Thus, for $b \geq \hat{b}$, the expected asset price declines in b. By equation (4), at $\hat{b}$ the forward contract price exceeds the expected spot price of the asset if the R&D firm invests in innovation. Consequently, for all $b \geq \hat{b}$ the forward contract price associated with the tender offer $T = (\hat{f}, \hat{b})$ exceeds the expected spot price of the asset.

Suppose the asset users have tentatively agreed to buy $\tilde{b}$ contracts, where $B \geq \tilde{b} > \hat{b}$. Asset user i contemplates replacing a forward contract with an additional purchase on the spot market, assuming all other asset users maintain their purchases of forward contracts. Asset user i's action has two consequences. First, one forward contract is traded for a spot market purchase. As the tender offer remains satisfied, the R&D firm conducts research, and the asset user can expect to save money on the purchase of the asset on the spot market. The asset user, however, is already buying multiple units on the spot market, and the expected price for each of these increases with the reduction in x. If the standard prisoners' dilemma structure holds for R&D (Assumption B), the individual asset user's benefit fails to justify a marginal contribution. An asset user would then choose to buy fewer forward contracts, and whenever $\tilde{b}$ exceeds $\hat{b}$, $\tilde{b}$ is not an equilibrium.

Define $b_{\sim i} = \hat{b} - b_i$ as the purchases of forward contracts by all asset users other than asset user i. If asset user i takes as given $b_{\sim i}$, then reducing b_i results in total offers for forward contracts of less than $\hat{b}$; no R&D is performed, and the expected unit price of the asset is p in the next period. The asset user then pays more for all units he planned to buy on the spot market, as well as the difference between $\hat{f}$ and p for asset units covered by the forward contracts. By Proposition 1, the forward price, $\hat{f}$ is less than p, at that price the asset owners strictly prefer to participate in the tender offer whenever $\hat{b} < B$:

Proposition 3. Let $T = (\hat{f}, \hat{b})$ be a tender offer satisfying equations (4.1) and (4.2), and suppose $b_{\sim i} + b_i = \hat{b}$, so asset user i is decisive. Then asset user i strictly prefers participating in the tender offer to foregoing the R&D program.

Existence of a subgame perfect equilibrium

Proposition 1 describes conditions for a tender offer to be time consistent and to satisfy both asset owners and the R&D firm. Proposition 4 establishes existence, and summarizes the results:

Proposition 4. Let $\mathcal{T}$ be the set of tender offers $T = (\hat{f},\ \hat{b})$ satisfying equations (2), (4.1), and (4.2). If Assumption A holds, $\mathcal{T}$ is non-empty. Furthermore, any $T \epsilon\ \mathcal{T}$ is associated with a subgame perfect Nash equilibrium with: (1) full subscription to the offer by asset users; (2) positive investment by the R&D firm; and (3) zero expected profits to the R&D firm.

Robustness

How robust are the results? From the perspective of the asset users, the equilibrium is analogous to the model in Bagnoli and Lipman (1989) on the private provision of a public good, and their results for robustness carry through. Specifically, the equilibrium is *not* robust to some mistakes by the asset users. But if we consider only undominated perfect equilibria for each tender offer *T*, the result is robust. Each asset user must believe that the mistakes other asset users make is to buy too few forward contracts rather than too many. Buying too many forward contracts is always dominated by buying too few, so that the refinement appears reasonable.

Relaxing risk neutrality expands the set of projects for which the forward-market mechanism can induce investment. Asset users who are risk-averse would buy more forward contracts than the minimum tender offer level, resulting in positive economic profits to the R&D firm. Alternatively, they will be willing to buy forward contracts for a higher price than would risk-neutral firms, and thus support projects where R&D is more expensive or less likely to succeed than they would under risk neutrality.

Pareto dominant tender offers

Because the R&D firm has zero expected profits, it is indifferent between the feasible tender offers. The asset users, however, are not. They expect to pay $(1 - R(x))p$ for $(B - \hat{b})$ units of the target asset and to pay $\hat{f}$ for the remaining $\hat{b}$ units, so their total cost is:

$$(6)\qquad TC(\hat{b}) = (1 - R(x^*))p(B - \hat{b}) + [(1 - R(x^*))p + x^*/\hat{b}]\,\hat{b} = (1 - R(x^*(\hat{b})))Bp + x^*(\hat{b}).$$

The cost equation (6) has a unique minimum, giving rise to a Pareto dominant tender offer:

Proposition 5: For any non-empty set $\mathcal{T}$ of feasible tender offers associated with an R&D program $R(x)$, (1) financial benefits increase with the number of forward contracts $\hat{b}$, (2) R&D investment increase with the number of forward contracts $\hat{b}$, and (3) there exists a unique Pareto dominant tender offer $T^* = (\hat{f},\ \hat{b})$, where $\hat{b} = B$ and $\hat{f}$ is defined by equation (4.1). For all feasible tender offers $T \epsilon\ \mathcal{T}$, the Pareto dominant tender offer results in maximum investment in R&D.

Contract costs

Imperfections in the contract regime modify these results. While a review of the institutions is beyond the scope of this paper, it is worth noting that enforcement and execution of contracts, like that of property rights, is costly. We briefly consider how two illustrative features, liquidity constraints and transaction costs, affect the Pareto dominant tender offer.

Liquidity constraints dog inventors. Financing costs for R&D can be high, favoring large corporate R&D firms, which can rely on profits or retained earnings to finance research (Hall and Lerner, 2010). Liquidity constraints pose a different type of problem for the forward-market mechanism. The sale of forward contracts can finance R&D. But should no innovation result, the R&D firm may need considerable resources to cover its liabilities to asset users. If the R&D firm can enter bankruptcy, asset users may demand collateral, and liquidity constraints can limit the R&D firm's ability to sell forward contracts.

This complication has two immediate implications. Some R&D firms may be unable to use the forward-market mechanism to conduct R&D. Second, the Pareto dominant tender offer described above involves maximum exposure for the R&D firm. If the project fails, the R&D firm is liable for Bp worth of assets to cover its forward position. The best tender offer may thus involve fewer contracts and less spending on R&D.

Transaction costs also modify the results of the previous section. Transaction costs typically follow a two-part tariff, increasing with both the number of contractual partners and the number of future market contracts signed. We consider here symmetric equilibria, with all asset users participating in the tender offer. The transaction costs then are composed of a fixed component, associated with the number of asset users, and a variable component.

The mechanism described so far ignored any fixed cost the R&D firm incurs prior to contracting. In the subsequent section we relax information symmetry and derive a mechanism that allows the R&D firm to profit from the forward contracts and thus conceivably cover such transaction costs. Alternatively, variable transaction costs can be accommodated in the simple model.

Let $C(b)$ be the variable component of the transaction costs, where $C'(b) > 0$.

The feasibility condition needs to be modified to state that the expected financial benefits suffice to cover investment costs and transaction costs for some number of forward market contracts:

Assumption A': There exists some positive investment level x and forward contracting level $b \leq B$ such that:

$$R(x)bp - C(b) - x \geq 0 \tag{7}$$

When Assumption A' holds, but transaction costs are high, there will be an interior maximum b for the expected financial benefits net of transaction costs. Define $\bar{b}$ to be the largest value of b for which Assumption A' holds. As before, a range of feasible tender offers leads to a subgame perfect equilibrium with positive R&D, and the optimal investment level $x^*(b)$ is increasing in b. In general, however, $\bar{b}$ will be less than B, and the Pareto dominant tender offer will be smaller than $\bar{b}$. Increased transaction costs thus reduce spending on R&D.

5. Asymmetric information

We so far considered symmetric information between the R&D firm and asset users. A more plausible situation is that the R&D firm has some private information about the R&D project. The efficiency of innovation mechanisms usually changes with information asymmetries. For example, with asymmetric information about cost, mechanisms to efficiently allocate contracts for research require competition among providers (Sappington,1982; Scotchmer,1999a; Scotchmer, 1999b). A prize-based system can be efficient in the presence of asymmetric cost information, but not in the absence of information about the value of the proposed innovation. When the rewards to innovation are based on technology benefits, asymmetric information about the value of the technology limits efficient mechanisms to the patent system or its close relatives (Chari, Golosov, and Tsyvinski, 2012).[5]

The forward-market mechanism can be robust to information asymmetries about the cost of R&D, or about its value to asset users. Depending on the extent of pecuniary benefits, a Nash equilibrium with high investment continues to exist. It differs from the full-information Nash equilibrium in that the R&D firm can use its informational advantage to obtain positive expected profits.

Private information about project cost

We consider first cost information. To focus on the asymmetry, suppose the R&D firm can invest in a single project which with probability R reduces the price of the price of the target asset to zero. The cost, $x\ \varepsilon\ [x^L, x^H]$ is known only to the R&D firm. Let $T = (f, b)$ be a tender offer that gives the R&D firm an incentive to conduct research for any cost in the possible range:

$$(8)\qquad f = (1-R)p + {}^{x^H}\!/_{b} \text{ and } f \le p.$$

The tender offer T is a Nash equilibrium if no asset user i has a unilateral incentive to buy fewer than b_i forward contracts, conditional on $b_i + b_{\sim i} = b$. Let θ^k be the probability that the R&D firm cancels the tender offer when the asset users subscribe to $b - k$ contracts:

$$\theta^k = prob\left\{\frac{b-k}{b}x^H < x\right\}$$

Then T is a Nash Equilibrium if:

$$(9)\qquad x^H\left[\frac{\theta^k b_i + (1-\theta^k)k}{b_i}\right] \le \theta^k RBp\ for\ k = 1, \dots, b_i$$

By Equation (5), Equation (9) holds when $\theta^k = 1$, as $B \ge b$. A necessary condition for T to be a Nash equilibrium is that (9) holds for $k = b_i$:

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[5] For example, the public sector could buy out valuable patents and place the technology in the public sector. See Kremer, 1998.

(10) $x^H \leq \theta^{b_i} RBp$

Thus, pecuniary benefits must be sufficiently large to cover the excess charges to asset users over the expected spot price, even when discounted by the probability that an asset user is decisive when he buys no forward contracts.

The value of θ^k is non-decreasing in *k*, while the second factor on the left-hand side of equation (9) increases in *k*. This factor reflects the increasing benefits for the asset user when he buys fewer and fewer forward contracts without being decisive. For each additional contract foregone, a non-decisive asset user saves the difference between the forward contract and the expected spot market price if R&D is undertaken. Depending on the distribution of *x*, equation (9) can become more or less stringent as *k* increases; moreover, the change in stringency need not be monotonic.

Suppose there is a sufficiently small probability an asset user who shirks by a single contract will be decisive, that shirking by one unit justifies its modest benefits. Suppose in addition that an asset user would refrain from shirking by *k* or more contracts. The R&D firm may be able to save the project by judiciously choosing a tender offer that involves fewer forward contracts and a higher share of the R&D cost charged to each contract.

Consider the tender offer $\tilde{T} = (\tilde{f}, \tilde{b})$ where $\tilde{b} = {}^{b}\!/_{2}, \tilde{f} = f + {}^{x^H}\!/_{b}$ and suppose $\tilde{f} \leq p$. This offer must satisfy equation (8). It also satisfies equation (10), as by construction $\theta^{\tilde{b}_i} = \theta^{b_i}$. But this tender offer avoids the condition (9) for tender offer *T* for *k* = *1* (and other odd values of *k*), which may suffice to induce the asset owner to fully subscribe to the tender offer. Alternatively, the R&D firm is indifferent between any tender offer satisfying (8). If any such tender offer is accepted, the R&D firm's expected profits is the difference between x^H and *x*. To summarize:

Proposition 6: When the R&D firm has private information about project cost, a Nash equilibrium tender offer with investment exists if the financial benefits are sufficiently large, and the worst (i.e., highest) possible cost is likely enough to dissuade asset users from free-riding. The R&D firm's expected profits are the difference between the maximum possible cost and the actual cost. For a particular project, we expect the tender offer to involve a minimal number of contracts, subject to satisfying equation (8).

Private information about the likely outcome of the project

We model an information asymmetry in the expected outcome of a project by fixing the cost of R&D at *x*. The R&D firm knows the true probability that the project succeeds, *R*, while asset users know only that $R \in [R^L, R^H]$. An equilibrium tender offer *T* = *(f, b)* must fund the worst outcome:

(11) $f = (1 - R^L)p + {}^{x}\!/_{b}$ and $f \leq p$.

Equation (11) is consistent with a Nash equilibrium if:

$$(12)\qquad [x + (\bar{R} - R^L)bp]\left[\frac{\theta^k b_i + (1-\theta^k)k}{b_i}\right] \leq \theta^k \bar{R} Bp \; for\; k = 1, \ldots, b_i,$$

where $\bar{R}$ is the expected value of R, conditional on $R > R^L$, and θ^k is the probability that the project is canceled when asset users buy only b-k forward contracts:

$$(13)\qquad \theta^k = prob\left\{(b-k)(\bar{R} - R^L)p - \frac{k}{b}x < 0\right\}$$

An asset user who buys fewer forward contracts, in the hope that the project will continue without them, may save when buying on the spot market. As before, the expected spot price does not include any share of the research cost x. In addition, when the realized value of R exceeds R^L, the expected spot price is less than the component of the forward contract intended to cover spot purchases by the R&D firm. The first term on the left-hand side of equation (12) incorporates this additional potential benefit from free-riding and it figures into the asset user's calculation that he is decisive in (13).

The issues that arise for asset owners when information about costs is asymmetric also apply to this case; but a tender offer with fewer forward contracts now has an additional advantage. As the asset owner makes up the difference in asset demand on the spot market, he, as well as the R&D firm, benefits from a better outcome R. Moreover, with fewer forward contracts, the asset owner is more likely to be decisive (equation (13)) because the R&D firm has smaller profits. Thus, asset owners are more likely to participate in a tender with fewer, more expensive, forward contracts.

The preferences over the tender contract of the asset owners and the R&D firm are in conflict. The R&D firm realizes profits from covering forward contracts with spot market contracts that it expects will be less expensive when $R > R^L$, and its profits increase in the number of forward contracts included in the tender offer. It will want to sell as many forward contracts as possible:

Proposition 7. When the R&D firm has private information about project outcome, a Nash equilibrium tender offer with investment exists if the financial benefits are sufficiently high, and the worst (i.e., lowest) possible outcome is likely enough to dissuade asset users from free-riding. The R&D firm's expected profits increase with the size of the tender offer. For a particular project, we expect the tender offer to involve a maximal number of contracts, subject to satisfying equations (11) and (12).

Asymmetric information typically undermines markets, and innovation markets are no exception. Under a patent system, inventors are either unable to obtain financing, or pay a premium for financing, and some worthy projects are priced out. Similarly here, asymmetric information rules out some projects that all parties would favor. Condition (9) fails to hold when the R&D firm knows that costs will be unusually high relative to benefits. Conditions (11) fails when the expected pecuniary benefits are small relative to costs. Unable to credibly convey that information to asset users, the R&D firm cannot arrange a tender offer that covers its expected costs, yet is a Nash equilibrium outcome for asset users. But if the projects are reasonably attractive -- costs are within a range that all parties believe is plausible, or the probable pecuniary value is high relative to costs -- the firm can both arrange financing and exploit its informational advantage.

6. Discussion

Shortcomings of the patent system have increased interest in other ways of incentivizing research and innovation. This paper develops a mechanism which supports innovation in the absence of intellectual property rights. More generally, it models the incentives to provide a public good (such as a technological innovation) when the provider can profit from a change in the price of an asset resulting from his investment. The mechanism described here focuses on the financial profits that allow the R&D firm to profit from forward contracts, rather than from selling the good it produces. The mechanism can generate incentives to invest in producing a public good, and to sell it at a low price.

The mechanism we consider has several advantages. First, it gives the R&D firm an incentive to invest, and the investment may be large.[6]

Second, it does not require a contract to specify any particular technological approach. Standard research financing arrangements (including both public subsidy programs and private venture capital) closely monitor the inventor's activities and restrict the extent to which he can diverge from his initial research investment plan. These restrictions can lead to costly delays or misallocation of resources, yet constitute a necessary tradeoff given the incentive conflicts usually present with outside financing for research.

Third, the mechanism promotes efficient ex post pricing. It ties profits to a complement to the innovation, so that the R&D firm's profits are greater the more widely used is the invention, and the lower the price charged its asset users. The R&D firm has an incentive to charge a low price for the good.

Fourth, the mechanism can overcome free riding. Polluters in the cap and trade example pay for what is in effect a public good: a polluter benefits from a reduction in the spot price following a

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[6] The high investment contrasts to results by Barrett (2005 and 2006), who considers the conditions under which countries will agree to treaties to promote research relating to climate change, even when no external enforcement is possible. Neither investment in abatement nor investment in research is discrete, but a threshold arises when each treaty member calculates that his exit will lead all remaining members to abandon the treaty. Barrett shows that both treaties and research programs form, but the participation and investment levels are typically very low.

successful innovation, even if the polluter had not bought a forward contract. The forward-contract mechanism can induce investment in a public good that is not discrete, via an incentive compatible choice of tender offer.

Fifth, though we allow R&D to be risky, we do not require any secrecy or private information: all information, including the likelihood that the R&D investment will succeed, is common knowledge at the time of contracting, thereby relaxing the restrictions in the speculation-based policies. Moreover, the mechanism is robust to limited private information about the project itself: either its cost or its likely success. In these cases, the R&D firm expects to make positive profits.

We explore the possibility of basing returns to innovation on pecuniary externalities rather than technology users. The beneficiaries of pecuniary externalities may promote socially efficient innovation incentives. The externalities increase with wide use and diffusion of the technology, promoting efficient pricing, efficient use, and possibly follow-on research. As one application to policy, our analysis above suggests an additional or perhaps different role for government-sponsored consortia: aiding the identification and collaboration of firms that could benefit from inexpensive provision of technology services by providing or using a good that is complementary to the innovation. The Carbon Capture and Sequestration consortium, according to this view, should include coal producers rather than utilities as financial partners, whereas Sematech should have included semiconductor users rather than their manufacturers as contractees for the semiconductor equipment manufacturers.

The forward-market mechanism grounds incentives to innovate in contract law rather than intellectual property law. While both legal systems are costly, the theoretical advantages explored in this paper suggest that it may be useful to consider an approach based on enforcement of private contracts rather than intellectual property.

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Appendix

Proposition 1: Let $T = (\hat{f},\ \hat{b}\,)$ be a tender offer such that

(A1) $\hat{f} = \left(1 - R\left(x^*(\hat{b})\right)p\right) + \frac{x^*(\hat{b})}{\hat{b}},$

where $x^*(\hat{b})$ is defined by equation (3). Then the firm will sell contracts and engage in R&D if and only if $b \geq \hat{b}$.

Proof. Assume that the R&D firm spends $x^*(b)$ on R&D if it sells b forward contracts. We show that for optimal x defined by equation (2) and a fixed value for f, $E(\pi)$ is increasing in b at $\hat{b}$.

(A2) $E(\pi) = \hat{f}b - \left(1 - R(x)\right)pb - x$

(A3) ${}^{\partial E(\pi)}\!/_{\partial b} = \hat{f} - (1 - R(x)p + pbR'(x)\frac{dx}{db} - \frac{dx}{db} = \left(\hat{f} - \left(1 - R(x)\right)p\right)$

As by equation (2) $R'(x) = {}^{1}\!/_{pb}$.

Substituting from (A1), (A3) = ${}^{x}\!/_{\hat{b}} > 0$.

It is straightforward to check that if $\hat{f}$ defined by equation (A1), expected profits are zero at $\hat{b}$, thus $E(\pi)$ is positive for $b > \hat{b}$ and negative for $b < \hat{b}$.

We next establish that if (4.2) holds, the R&D firm will spend $x^*(b)$ for all $b \geq \hat{b}$. Equation (4.2) is equivalent to:

(A4) $x^*(\hat{b}) \leq p\hat{b}R\left(x^*(\hat{b})\right)$

Define $H(b) = bpR(x(b)) - x(b)$. By (A4), $H(\hat{b}) \geq 0$. It is sufficient to show that $H'(b) > 0$ for $\hat{b} \leq b \leq B$

(A5) $H'(b) = pR(x^*(b) + bp\ R'(x^*(b))x^{*\prime}(b) - x^{*\prime}(b)$

substituting for $R'(x^*(b)) = 1/bp$,

(A6) $H'(b) = pR(x^*(b)) > 0.$

Proposition 2. If there exists a feasible subscription level $\underline{b}$, where $0 < \underline{b} \leq B$ and $x^*(\underline{b}) = p\underline{b}R(x^*(\underline{b}))$. Then for all $\hat{b}$ such that $\underline{b} \leq \hat{b} \leq B$, $x^*(\hat{b}) \leq p\hat{b}R(x^*(\hat{b}))$.

Proof: see (A4), (A5), (A6).

Proposition 3. Let $T = (\hat{f},\ \hat{b}\,)$ be a tender offer satisfying equations (4.1) and (4.2), and suppose asset user i is decisive so that $b_{\sim i} + b_i = \hat{b}$. Then asset user i strictly prefers participating in the tender offer to foregoing the R&D program.

Proof: Asset user i strictly prefers the tender offer to no R&D if:

(A7) $b_i f + (B_i - b_i)(1 - R(x^*(b))p < B_i p$

(A7) is equivalent to:

(A8) $b_i\left[p\frac{RB_i+(1-R)b_i}{b_i} - f\right] > 0$

As $p \geq f$, (A8) holds for $b_i < B_i$.

At $\hat{b} = B$, $\hat{f} = (1 - R(x^*(B))p + \frac{x^*(B)}{B}$

so: $p - \hat{f} = B[R(x^*(B))pB - x^*(B)] > 0$ by Assumption A.

Proposition 4. Let $\mathcal{T}$ be the set of tender offers $T = (\hat{f},\ \hat{b}\,)$ satisfying equations (2), (4.1), and (4.2). If Assumption A holds, $\mathcal{T}$ is non-empty. Furthermore, any $T \epsilon \mathcal{T}$ is associated with a Nash equilibrium with: (1) full subscription to the offer by asset users; (2) positive investment in research; and (3) zero expected profits to the R&D firm.

Proof:

Consider the tender offer $T = (F,\ B)$ where $F = \left(1 - R\left(x^*(B)\right)\right)p + \frac{x^*(B)}{B}$. $x^*(B)$ maximizes $FB - (1-R(x))pB - x$, so $x^*(B)$ also maximizes $R(x)pB - x$. By Assumption A, there exists x such that $x < R(x)pB$, thus, $x^*(B) < R(x^*(B))pB$, so conditions 2, 4.1, and 5 are satisfied at $T=(F,B)$, and $\mathcal{T}$ is non-empty. The remaining parts of the Theorem follow directly from Propositions 1, 2, and the discussion in the text.

Proposition 5: For any non-empty set $\mathcal{T}$ of feasible tender offers associated with an R&D program R, there exists a unique undominated equilibrium $T^* = (\hat{f},\ \hat{b}\,)$ where $\hat{b} = B$ and $\hat{f}$ is defined by equation (4). The undominated equilibrium results in maximum investment in R&D for all feasible tender offers $T \epsilon \mathcal{T}$.

Proof:

1. Total cost to the asset users declines in b:

$$TC'(b) = -R'(x)Bpx'(b) + x'(b) = -(1/pb)Bpx'(b) + x'(b)$$

$$= x'(b)\,((b-B)/b) \leq 0.$$ as $x'(b) > 0$ and $b \leq B$.

So, the total cost to the asset users is minimized at $b = B$.

2. The forward contract price declines with b, reaching a minimum when $b = B$, or when all asset users buy forward contracts for all units of the asset they need:

$$\frac{df}{db} = p(-R'\big(x^*(b)\big)x^{*\prime}(b) + \frac{x^{*\prime}(b)}{b} - \frac{x^*(b)}{b^2} = -\frac{x^*(b)}{b^2} < 0$$

(substitute $R'(x) = 1/pb$ at $x^*(b)$)

3. R&D investment x^* increases with b, reaching a maximum when $b = B$ and all asset users buy contracts for all units of the asset they use:

$dx^*/db > 0$. *(See equation (3), in text).*

Propositions 6 and 7: see discussion in text.